Unpolarized TMDs: extractions and predictive power

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INT 18-3
Probing nucleons and nuclei in high-energy collisions

Transverse spin and TMDs

Oct. 8th, 2018

Outline of the talk

1) TMDs and their evolution

2) first attempt to a global fit

3) predictive power vs
relevance of nonperturbative corrections

4) outlook

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TMDs & their evolution

References (intro and reviews) :

- “The 3D structure of the nucleon” **EPJ A (2016) 52**
- J.C. Collins “**Foundations of perturbative QCD**”
- material from the TMD collaboration **summer school**
- ...

Quark TMD PDFs

$$\Phi_{ij}(k,P;S,T) \sim \text{F.T.}\ \langle PS \ |\ \bar{\psi}_j(0)\ U_{[0,\xi]}\ \psi_i(\xi)\ |PS\ \rangle_{|LF}$$

	U	L	T
Quarks	γ^+	$\gamma^+\gamma^5$	$i\sigma^{i+}\gamma^5$
U	$\boldsymbol{f_1}$		$h_1^\perp$
L		$\boldsymbol{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\boldsymbol{h_1}$, $h_{1T}^\perp$

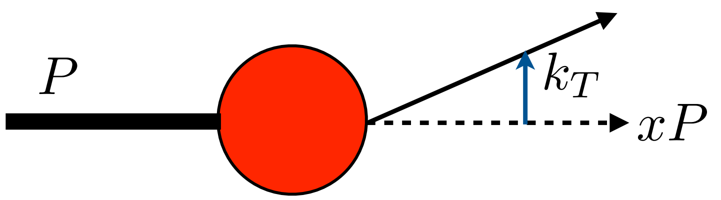
Sivers TMD PDF

unpolarized TMD PDF

similar table for **gluons** and for **fragmentation**

bold : also collinear

red : time-reversal odd (universality properties)



extraction of a **quark**
not collinear with the proton

encode all the possible
spin-spin and **spin-momentum**
correlations
between the proton
and its constituents

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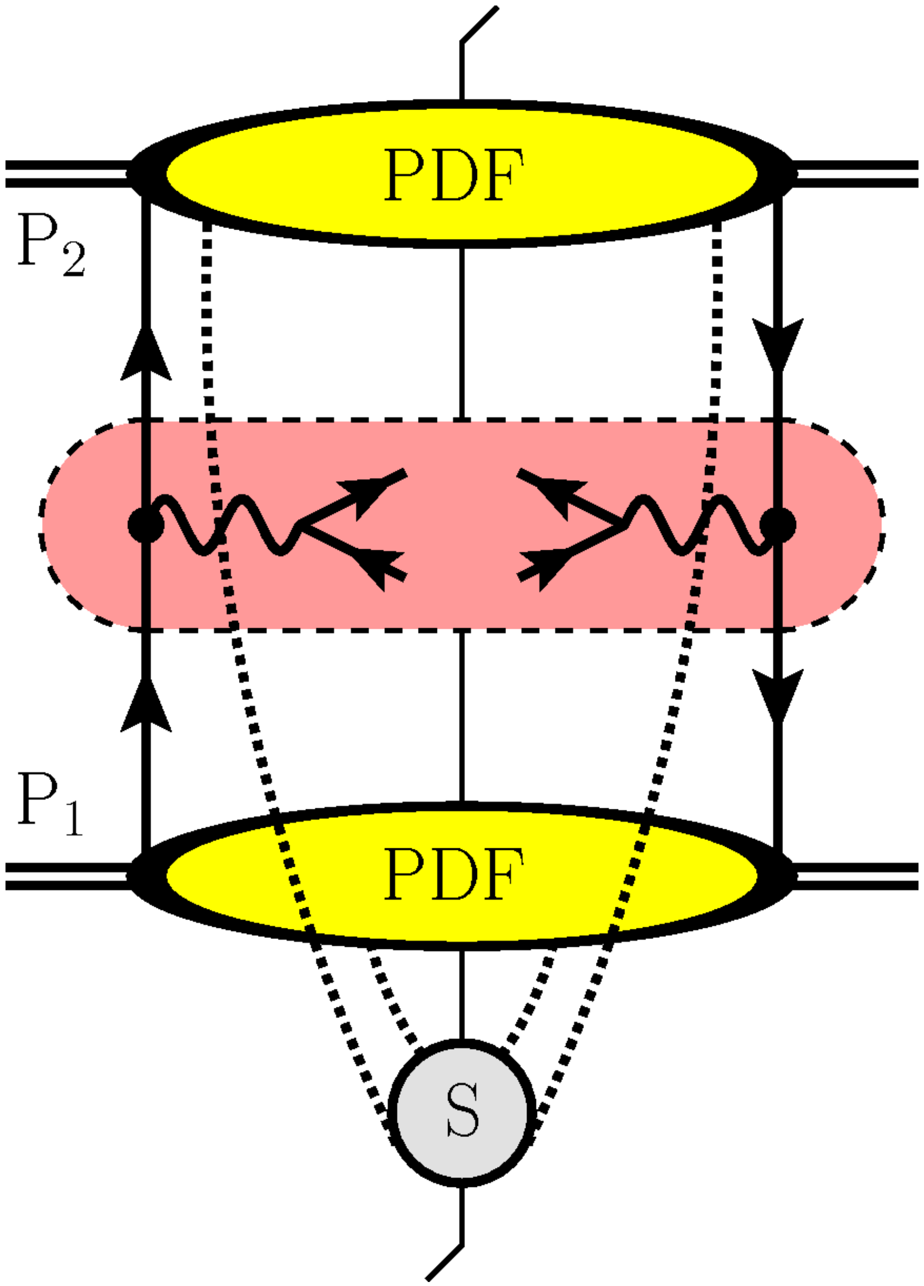
Factorization and evolution

$p\,p \to \ell\,\bar{\ell}\,X$



In certain processes
the cross section can be **factorized**
in contributions characterized by a specific
scaling of the momenta

$$d\sigma \sim \mathcal{H}\; f_1^{bare}\; f_1^{bare}\; \mathcal{S}$$
$$\sim \mathcal{H}\; f_1\; f_1$$

renormalized TMD PDF :

IR div. : long-distance physics
UV div. and **rapidity div.** cancelled
by UV-renormalization and soft factor S

$$f_1(x, k_T^2; \mu, \zeta)$$

Evolution with respect to two scales

Evolution of TMDs

$$f_1^a(x, b_T^2, \mu_f, \zeta_f) = f_1^a(x, b_T^2, \mu_i, \zeta_i)$$

b_T, Fourier conjugate of k_T

two "evolution scales"

$$\times \exp\left\{ \int_{\mu_i}^{\mu_f} \frac{d\mu}{\mu} \gamma_F \left[\alpha_s(\mu), \frac{\zeta_f}{\mu^2} \right] \right\}$$

evolution in mu
$\mu_i \to \mu_f$

$$\times \left(\frac{\zeta_f}{\zeta_i} \right)^{-K(b_T, \mu_i)}$$

evolution in zeta
$\zeta_i \to \zeta_f$

Input TMD distribution can be **expanded at low bT** onto a basis of collinear distributions

$$f_1^a(x, b_T^2, \mu_i, \zeta_i) = \sum_b C_{a/b}(x, b_T^2, \mu_i, \zeta_i) \otimes f_b(x, \mu_i)$$

A sensible choice is to set the initial and final scale as:

$$\zeta_i = \mu_i^2 = 4e^{-2\gamma_E}/b_T^2 \equiv \mu_b^2$$

$$\zeta_f = \mu_f^2 = Q^2$$

Evolution of TMDs

$$f_1^a(x, b_T^2, \mu_f, \zeta_f) = f_1^a(x, b_T^2, \mu_i, \zeta_i)$$

b_T, Fourier conjugate of k_T

two "evolution scales"

$$\times \exp\left\{ \int_{\mu_i}^{\mu_f} \frac{d\mu}{\mu} \gamma_F \left[\alpha_s(\mu), \frac{\zeta_f}{\mu^2} \right] \right\}$$

evolution in mu
$\mu_i \to \mu_f$

$$\times \left(\frac{\zeta_f}{\zeta_i} \right)^{-K(b_T, \mu_i) \; - g_K(b_T, \{\lambda\})}$$

evolution in zeta
$\zeta_i \to \zeta_f$

need corrections at large bT

Input TMD distribution can be **expanded at low bT** onto a basis of collinear distributions

$$f_1^a(x, b_T^2, \mu_i, \zeta_i) = \sum_b C_{a/b}(x, b_T^2, \mu_i, \zeta_i) \otimes f_b(x, \mu_i) \;\; F_{NP}^a(x, b_T; \{\lambda\})$$

A sensible choice is to set the initial and final scale as:

$$\zeta_i = \mu_i^2 = 4e^{-2\gamma_E}/b_T^2 \equiv \mu_b^2$$
$$\zeta_f = \mu_f^2 = Q^2$$

“Global” analysis

References :

- Bacchetta, Delcarro, Pisano, Radici, **AS**: JHEP 1706 (2017) 081

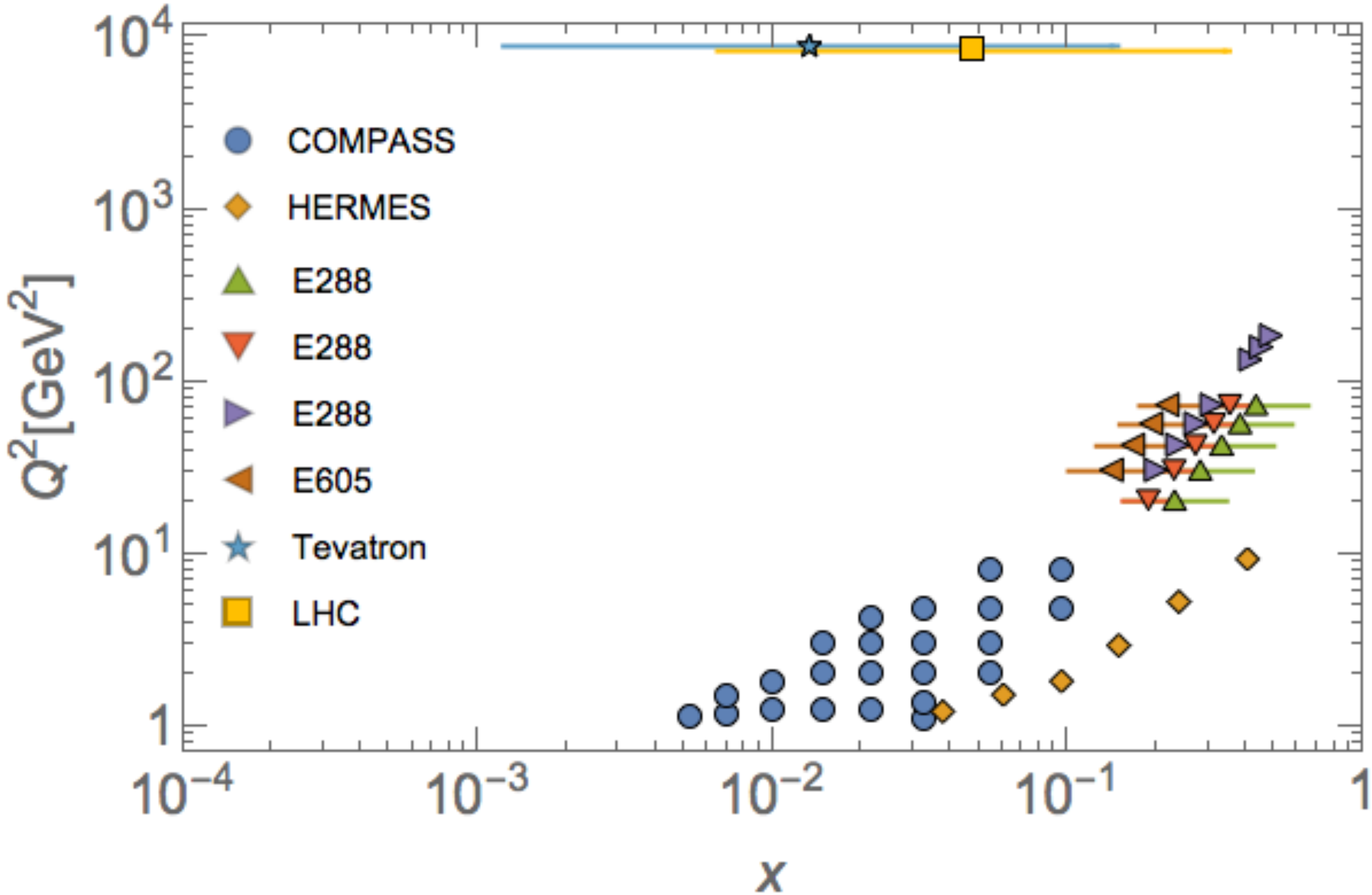
What do we know ?

(only a selection of results!)

	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	✘	✘	✔	✔	98
Pavia 2013 (+Amsterdam, Bilbao) arXiv:1309.3507	No evo (QPM)	✔	✘	✘	✘	1538
Torino 2014 (+JLab) arXiv:1312.6261	No evo (QPM)	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
Pavia 2017 arXiv:1703.10157	LO-NLL	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLO-NNLL	✘	✘	✔	✔	309

[courtesy A. Bacchetta]

Data sets and kinematic coverage



Electron-positron annihilation data are still missing
(only some azimuthal asymmetries are available)

crucial for analyses
of TMD FFs

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Features

	Framework	HERMES	COMPASS	DY	Z production	N of points
Pavia 2017 arXiv:1703.10157	LO-NLL	✔	✔	✔	✔	8059

PROs

almost a **global fit** of quark unpolarized TMDs

includes **TMD evolution**

replica (bootstrap) fitting methodology

kinematic dependence in intrinsic part of TMDs

intrinsic momentum: **beyond the Gaussian** assumption

CONs

no “pure” info on TMD FFs

accuracy of TMD evolution : not the state of the art

only “low” transverse momentum (no fixed order and Y-term)

flavor separation in the transverse plane : problematic

Intrinsic transverse momentum

$$f^a_{1NP}(x, k_\perp^2) = \frac{1}{\pi} \frac{(1+\lambda k_\perp^2)}{g_{1a} + \lambda g_{1a}^2} \; e^{-\frac{k_\perp^2}{g_{1a}}}$$

$$\hat{x} = 0.1$$

$$g_1(x) = N_1 \frac{(1-x)^\alpha x^\sigma}{(1-\hat{x})^\alpha \hat{x}^\sigma}$$

weighted sum of two Gaussian distributions:
same widths for TMD PDFs
different widths for TMD FFs

There are **11 free parameters**
in a flavor independent scenario
(one for evolution)

$$D_{1NP}^{a\to h}(z, P_\perp^2) = \frac{1}{\pi} \frac{1}{g_{3a\to h} + (\lambda_F/z^2) g_{4a\to h}^2} \left(e^{-\frac{P_\perp^2}{g_{3a\to h}}} + \lambda_F \frac{P_\perp^2}{z^2} \; e^{-\frac{P_\perp^2}{g_{4a\to h}}} \right)$$

$$\hat{z} = 0.5$$

$$g_{3,4}(z) = N_{3,4} \frac{(z^\beta + \delta)(1-z)^\gamma}{(\hat{z}^\beta + \delta)(1-\hat{z})^\gamma}$$

Inspired by **model calculations**:
Matevosyan et al.
Phys. Rev. D85, 014021 (2012), 1111.1740
Bacchetta et al.
Phys. Lett. B659, 234 (2008), 0707.3372
Bacchetta at al.
Phys. Rev. D65, 094021 (2002), hep-ph/0201091

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Models – evolution and b_T regions

$$g_K(b_T; g_2) = -g_2 \frac{b_T^2}{2}$$

Large bt correction to evolution
(other functional forms to be explored)

$$\hat{b}(b_T; b_{\min}, b_{\max}) = b_{\max} \left(\frac{1 - e^{-b_T^4/b_{\max}^4}}{1 - e^{-b_T^4/b_{\min}^4}} \right)$$

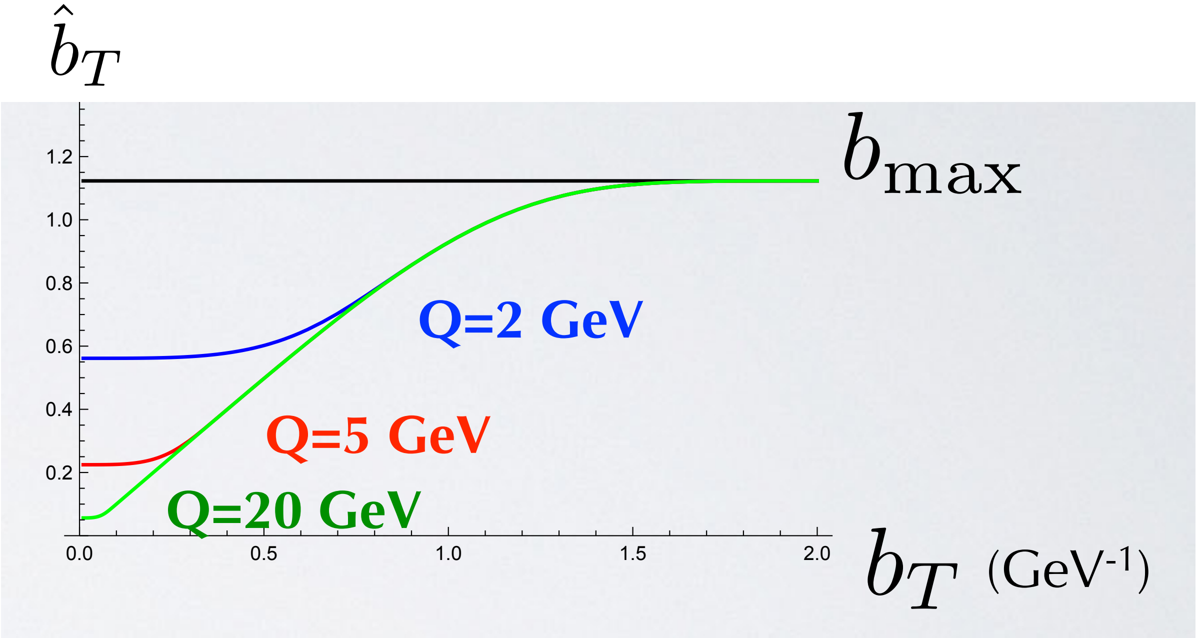
$b_{\max}$, $b_T \to +\infty$ avoid Landau pole

$b_{\min}$, $b_T \to 0$ recover collinear fact.

$b_{\min} \sim 1/Q$, $\mu_{\hat{b}} < Q$

Regularization needed to **recover the cross section integrated over qT** in collinear factorization.

Crucial from the **theory** point of view and for the **phenomenology of SIDIS (low Q)**



Data sets and selections – SIDIS

	HERMES $p \to \pi^+$	HERMES $p \to \pi^-$	HERMES $p \to K^+$	HERMES $p \to K^-$
Reference	[61]			
Cuts	$Q^2 > 1.4$ GeV^2 $0.2 < z < 0.7$ $P_{hT} < \text{Min}[0.2\ Q, 0.7\ Qz] + 0.5$ GeV			
Points	190	190	189	187
Max. Q^2	9.2 GeV^2			
x range	$0.06 < x < 0.4$			

TMD factorization
($P_{hT}^2/z^2 \ll Q^2$)

avoid target fragmentation [?]
(low z)
and exclusive contributions [?]
(high z)

Problem with normalization
in the previous release

	HERMES $D \to \pi^+$	HERMES $D \to \pi^-$	HERMES $D \to K^+$	HERMES $D \to K^-$	COMPASS $D \to h^+$	COMPASS $D \to h^-$
Reference	[74]				[75]	
Cuts	$Q^2 > 1.4$ GeV^2 $0.20 < z < 0.74$ $P_{hT} < \text{Min}[0.2\ Q, 0.7\ Qz] + 0.5$ GeV					
Points	190	190	189	189	3125	3127
Max. Q^2	9.2 GeV^2				10 GeV^2	
x range	$0.04 < x < 0.4$				$0.005 < x < 0.12$	
Notes					Observable: $m_{\text{norm}}(x, z, \boldsymbol{P}_{hT}^2, Q^2)$, eq. (3.1)	

Agreement data-theory

Flavor independent scenario

Flavor independent configuration | 11 parameters

Points	Parameters	χ^2	χ^2/d.o.f.
8059	11	12629 ± 363	1.55 ± 0.05

	HERMES $p \to \pi^+$	HERMES $p \to \pi^-$	HERMES $p \to K^+$	HERMES $p \to K^-$
Points	190	190	189	187
χ^2/points	4.83	2.47	0.91	0.82

Hermes P/D into π+:
problems at low z

	HERMES $D \to \pi^+$	HERMES $D \to \pi^-$	HERMES $D \to K^+$	HERMES $D \to K^-$	COMPASS $D \to h^+$	COMPASS $D \to h^-$
Points	190	190	189	189	3125	3127
χ^2/points	3.46	2.00	1.31	2.54	1.11	1.61

	E288 [200]	E288 [300]	E288 [400]	E605
Points	45	45	78	35
χ^2/points	0.99	0.84	0.32	1.12

	CDF Run I	D0 Run I	CDF Run II	D0 Run II
Points	31	14	37	8
χ^2/points	1.36	1.11	2.00	1.73

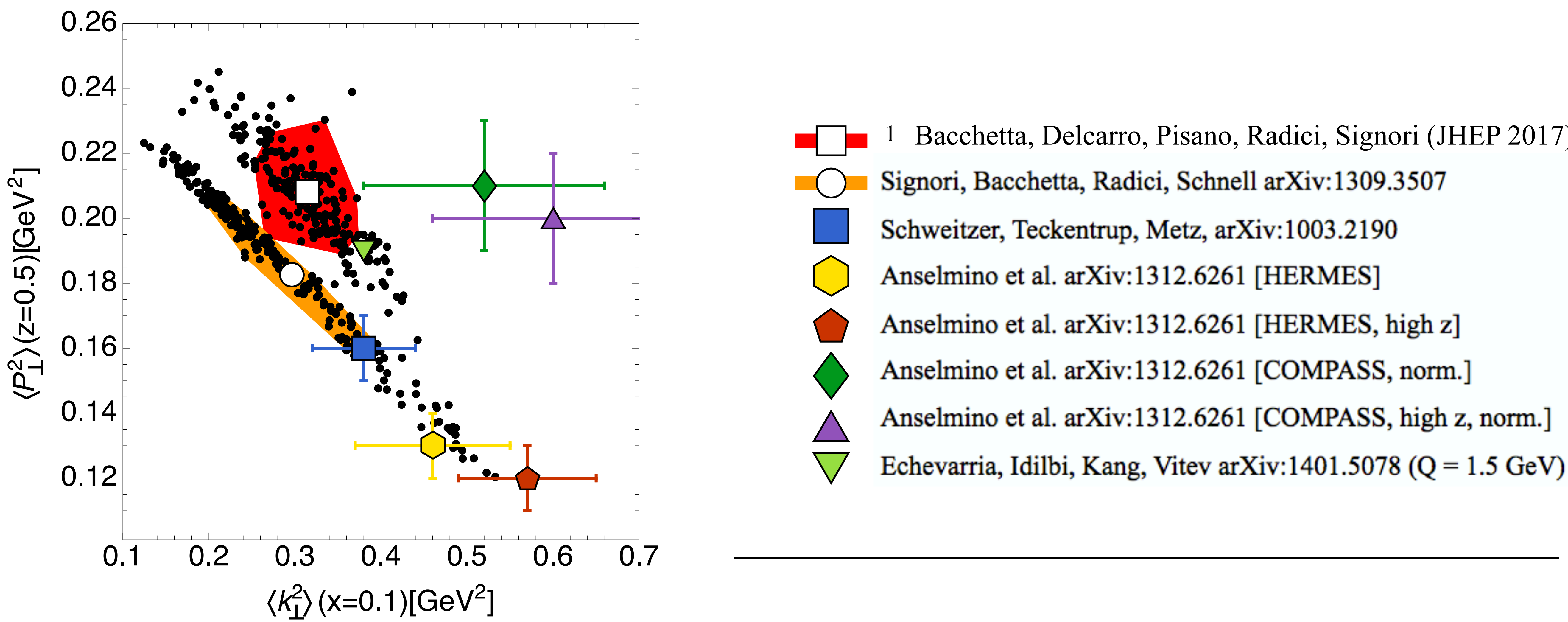
Hermes kaons better than pions:
larger uncertainties from FFs

Compass : better agreement due to
#points and normalization

**Let's see what
happens with the new data**

Average transverse momenta

Flavor ind. scenario



Red/orange regions : **68% CL** from replica method

Inclusion of **DY/Z diminishes the correlation**

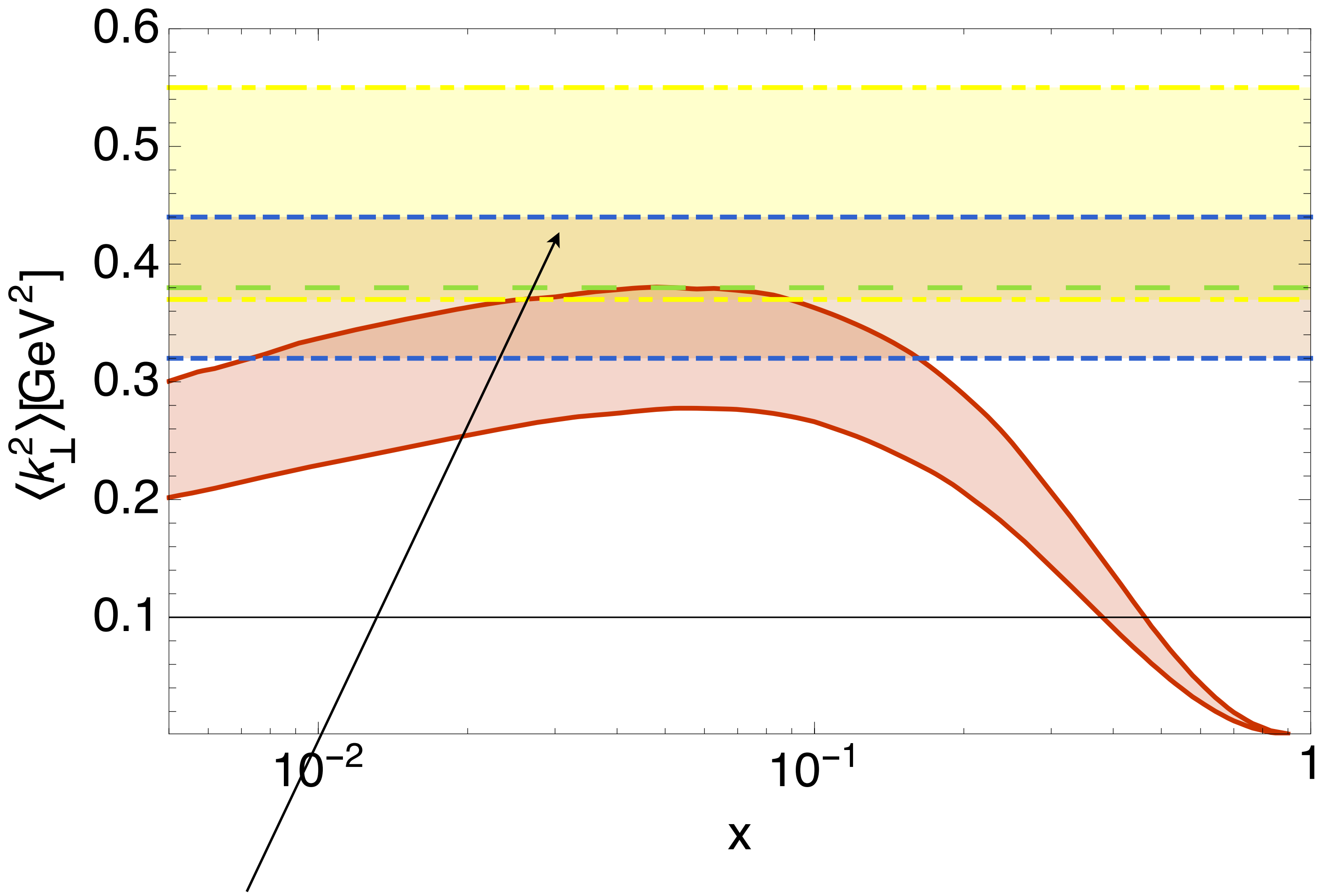
Inclusion of **Compass** increases the $\langle P_\perp^2 \rangle$ and reduces its spread

e+e- data would further reduce the correlation

Kinematic dependence

$$\langle k_\perp^2 \rangle(x) = \frac{\int d^2k_\perp \; k_\perp^2 \; f_1^a(x, k_\perp^2, Q = 1 \text{ GeV})}{\int d^2k_\perp \; f_1^a(x, k_\perp^2, Q = 1 \text{ GeV})}$$

Average square transverse momentum in TMD PDF



x-independent extractions

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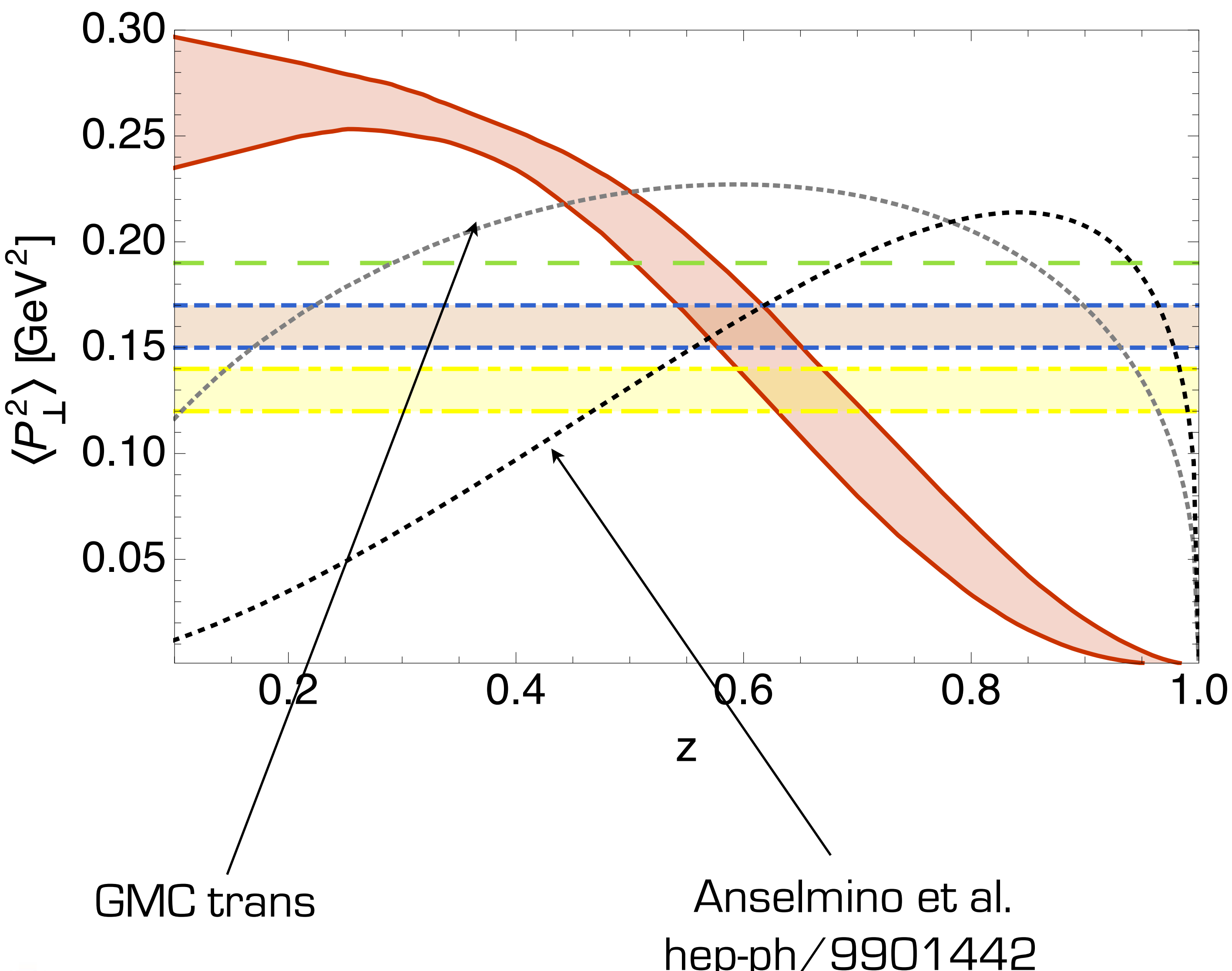
Flavor-independent scenario: no differences in quark/hadron flavor

Kinematic dependence

$$\langle P_\perp^2 \rangle(z) = \frac{\int d^2 P_\perp \; P_\perp^2 \; D_1^{a\to h}(z, P_\perp^2, Q = 1 \text{ GeV})}{\int d^2 P_\perp \; D_1^{a\to h}(z, P_\perp^2, Q = 1 \text{ GeV})}$$

Average square transverse momentum in TMD FF



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Flavor-independent scenario: no differences in quark/hadron flavor

z-dependence : important to fit the data

What's next

Urgent things we need:

- **SIDIS**: distinction of different fragmentation mechanism
- **SIDIS**: NLO description of low qT and high qT data (separately)

- all processes: **matching** low and high qT
(actually we could also start from high qT to describe data)

- independent extractions of **TMD FFs**: formalism but no data

- **gluon TMDs**: we have the (effective) formalism and the data

- a faithful **Monte Carlo** implementation of TMD sensitive processes

What about TMD FFs ?

Forthcoming **unpolarized data** with transverse momentum dependence:

1) Belle-2 : e+e- to h X (TM dependence with respect to thrust axis)
   collinear factorization ? TMDs ?
2) Belle-2 : e+e- to h1 h2 X - Definitely TMD factorization
3) BES-3 … ?

From the **theory viewpoint** we are working on the formalism, to prepare the ground for forthcoming extractions:

- **high-qT** limit in **collinear** factorization
- **low-qT** limit in **TMD** factorization

E. Moffat, T. Rogers, AS

Comparison with Pythia pseudo data for the moment,

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Gluon TMDs

gluon-gluon correlator

$$\Gamma^{\alpha\beta}(x,\mathbf{k}_T) \sim \text{F.T.}\ \langle P| F^{+\alpha}(0)\ U_{[0,\xi]}\ F^{+\beta}(\xi)\ U'_{[\xi,0]} |P\rangle_{|\xi^+=0}$$

Wilson loop correlator

$$\Gamma_0(x,\mathbf{k}_T) \sim \delta(x)\ \text{F.T.}\ \langle P| U^{[+]}_{[0,\xi]}\ U^{[-]}_{[\xi,0]} |P\rangle_{|\xi^+=0}$$

Boer, Cotogno, van Daal, Mulders, AS, Zhou
JHEP 1610 (2016) 013

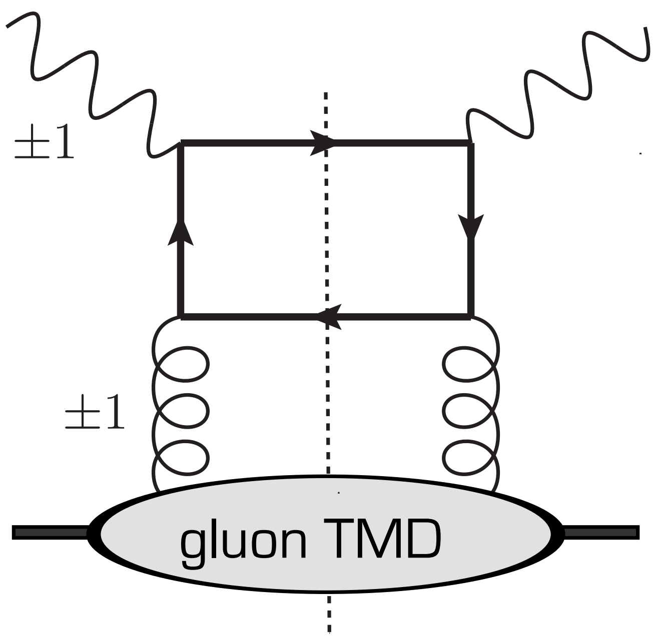
	Ref. [30]	Ref. [7]	Rank	T	C	Limit $x \to 0$
xf_1	xf_1	xG	0	even	even	$e^{(1)}$
$xh_1^\perp$	$xh_1^\perp$	$xH^\perp$	2	even	even	e
xg_1	xg_{1L}	$-x\Delta G_L$	0	even	odd	0
$xh_{1L}^\perp$	$xh_{1L}^\perp$	$-x\Delta H_L^\perp$	2	odd	even	0
$xf_{1T}^\perp$	$xf_{1T}^\perp$	$-xG_T$	1	odd	odd	$e_T^{(1)}$
xg_{1T}	xg_{1T}	$-x\Delta G_T$	1	even	even	0
xh_1	$xh_{1T} + xh_{1T}^{\perp(1)}$	$-x\Delta H_T$	1	odd	odd	$e_T^{(1)}$
$xh_{1T}^\perp$	$xh_{1T}^\perp$	$-x\Delta H_T^\perp$	3	odd	odd	$-e_T$
xf_{1LL}			0	even	even	$e_{LL}^{(1)}$
$xh_{1LL}^\perp$			2	even	even	e_{LL}
xf_{1LT}			1	even	odd	$e_{LT}^{(1)}/2$
xg_{1LT}			1	odd	even	0
xh_{1LT}			1	even	odd	$e_{LT}^{(1)}/2$
$xh_{1LT}^\perp$			3	even	odd	$-e_{LT}$
xf_{1TT}			2	even	even	$e_{TT}^{(1)}/3$
xg_{1TT}			2	odd	odd	0
xh_{1TT}			0	even	even	$e_{TT}^{(2)}$
$xh_{1TT}^\perp$			2	even	even	$-2\,e_{TT}^{(1)}/3$
$xh_{1TT}^{\perp\perp}$			4	even	even	e_{TT}

Table 1. An overview of the leading twist gluon TMDs for unpolarized, vector polarized, and tensor polarized hadrons. In the second and third column, the names of the functions in this paper are compared to the ones in refs. [7, 30]. In the fourth column we list the rank of the function. Furthermore, we list the properties (even/odd) under time reversal (T) and charge conjugation (C), see appendix A. In the last column it is indicated to which e-type function the TMD reduces in the limit $x \to 0$. As a shorthand, we use the moment notation $f_{\ldots}^{(n)}(x,\boldsymbol{k}_T^2) \equiv [\boldsymbol{k}_T^2/(2M^2)]^n f_{\ldots}(x,\boldsymbol{k}_T^2)$.

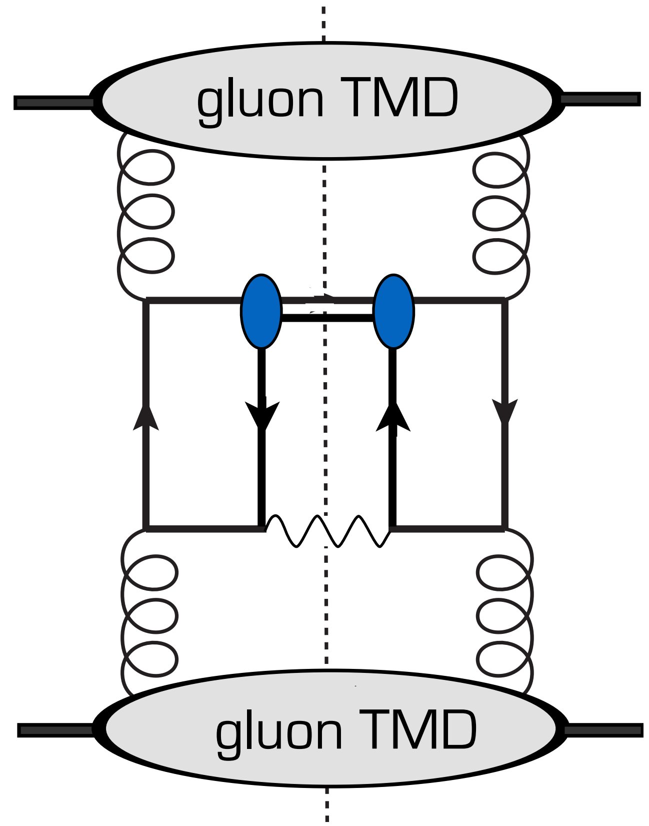
Gluon TMDs

$e\,p \to e \text{ jet jet } X$

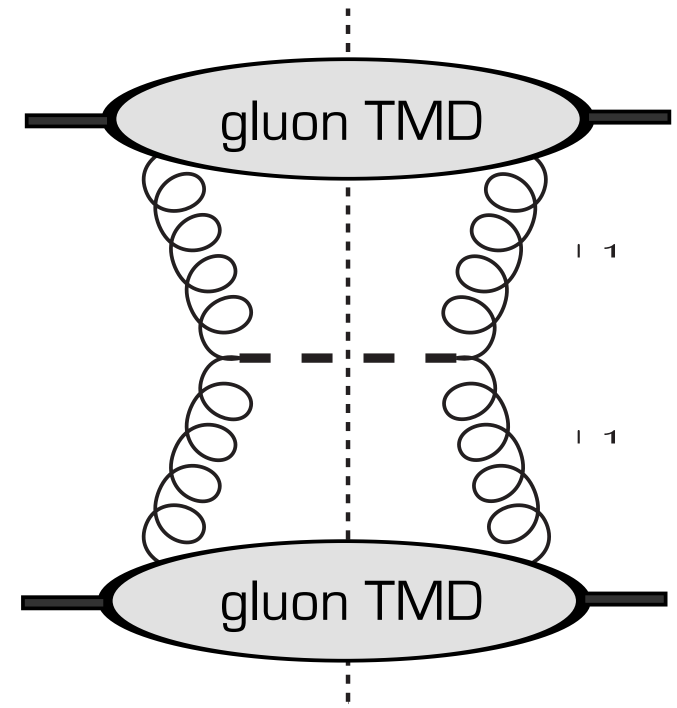
EIC !



$p\,p \to J/\psi\,\gamma\,X$



$p\,p \to \eta_c\,X$



- factorization properties in effective theories
- no extractions beyond parton model yet

See dedicated talks during the workshop

Predictive power

References :

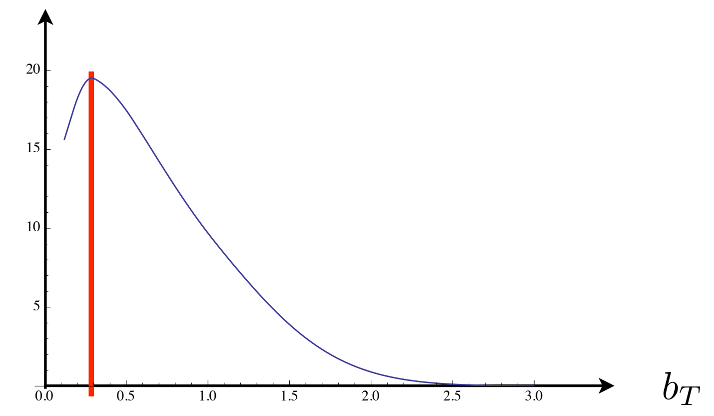
- Parisi, Petronzio: Nucl. Phys. B154, 427 (1979)
- Collins, Soper, Sterman: Nucl. Phys. B250, 199 (1985)
- Qiu, Berger: Phys. Rev. Lett. 91, 222003 (2003)
- Grewal, Kang, Qiu, **AS**: in preparation

Saddle point approximation

Given a generic function $f \in C^2(a,b)$ and a positive constant A

Given x_0, maximum in (a,b) for f :

$$I(x_0, A) = \int_a^b dx\; e^{Af(x)} = e^{Af(x_0)} \sqrt{\frac{2\pi}{A(-f''(x_0))}} \left(1 + \mathcal{O}\left(\frac{1}{A}\right)\right)$$



Saddle point approximation

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Given x_0, maximum in (a,b) for f :

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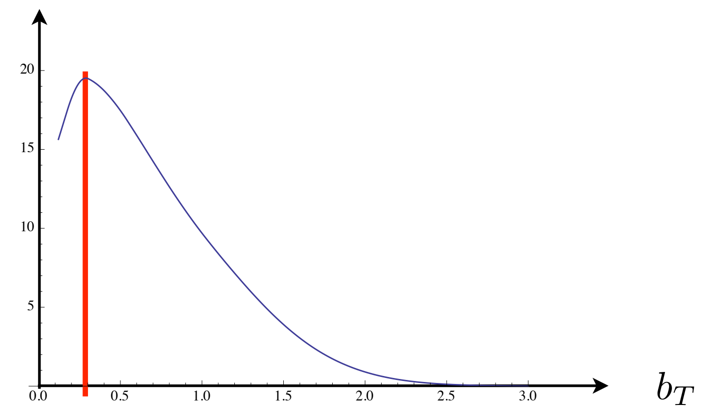


Let's apply this to a TMD PDF evaluated at $k_T = 0$:

$$f_1^a(x, k_T; \mu_f, \zeta_f) = \text{F.T.}\left[f_1^a(x, b_T; \mu_f, \zeta_f)\right]$$

$$f_1^a(x, k_T = 0; \mu_f, \zeta_f) = \frac{1}{4\pi} \int_{-\infty}^{+\infty} d(\ln b_T^2) \exp\left\{ \int_{\mu_i}^{\mu_f} \frac{d\mu}{\mu} \gamma_F \left[\alpha_s(\mu), \frac{\zeta_f}{\mu^2}\right] - K(b_T, \mu_i) \ln \frac{\zeta_f}{\zeta_i} + \ln b_T^2 + \ln\left[\sum_b C_{a/b} \otimes f_b\right]\right\}$$

Saddle point of the TMD PDF :
stationary point of the exponent

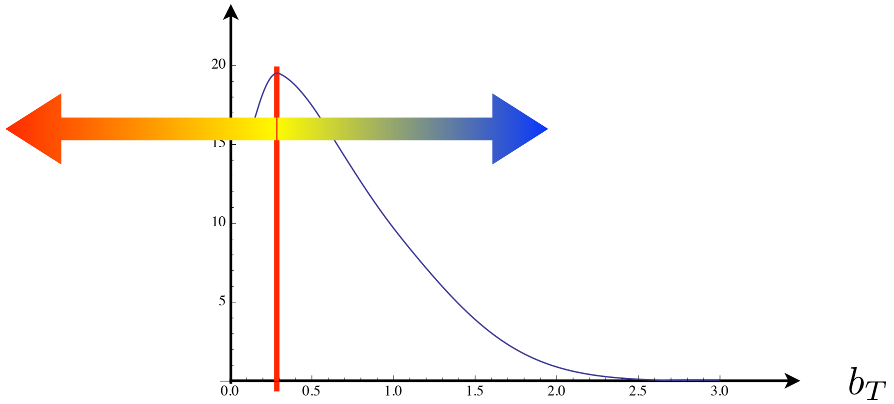
Determination of the saddle point

$$\frac{d}{db_T}\Bigg\{\int_{\mu_i}^{\mu_f}\frac{d\mu}{\mu}\gamma_F\left[\alpha_s(\mu),\frac{\zeta_f}{\mu^2}\right]$$
$$-K(b_T,\mu_i)\ln\frac{\zeta_f}{\zeta_i}$$
$$+\ln b_T^2$$
$$+\ln\left[\sum_b C_{a/b}(x,b_T^2,\mu_i,\zeta_i)\otimes f_b(x,\mu_i)\right]\Bigg\}_{b_T=b_T^{sp}}=0$$

Generate the **scale-dependence** of the saddle point

Generates the **x-dependence** of the saddle point

The **lower** the **saddle point**, the more the **TMD PDF is perturbatively dominated** : strong predictive power



The **higher** the **saddle point** (bT > bmax), the more the **nonperturbative corrections are important**

Determination of the saddle point

$$\frac{d}{db_T}\left\{\int_{\mu_i}^{\mu_f}\frac{d\mu}{\mu}\gamma_F\left[\alpha_s(\mu),\frac{\zeta_f}{\mu^2}\right]\right.$$

$$-K(b_T,\mu_i)\ln\frac{\zeta_f}{\zeta_i}$$

$$+\ln b_T^2$$

$$\left.+\ln\left[\sum_b C_{a/b}(x,b_T^2,\mu_i,\zeta_i)\otimes f_b(x,\mu_i)\right]\right\}_{b_T=b_T^{sp}}=0$$

Generate the **scale-dependence** of the saddle point

Parisi and Petronzio (1979) and Collins, Soper, Sterman (1982) : the same analysis at the level of the cross section, **neglecting the x-dependent part**:

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Determination of the saddle point

$$\frac{d}{db_T}\Bigg\{\int_{\mu_i}^{\mu_f}\frac{d\mu}{\mu}\gamma_F\left[\alpha_s(\mu),\frac{\zeta_f}{\mu^2}\right]$$

$$- K(b_T,\mu_i)\ln\frac{\zeta_f}{\zeta_i}$$

$$+ \ln b_T^2$$

$$+ \ln\left[\sum_b C_{a/b}(x,b_T^2,\mu_i,\zeta_i)\otimes f_b(x,\mu_i)\right]\Bigg\}_{b_T=b_T^{sp}} = 0$$

Generate the **scale-dependence** of the saddle point

Parisi and Petronzio (1979) and Collins, Soper, Sterman (1982) : the same analysis at the level of the cross section, **neglecting the x-dependent part**:

Conclusion : the large bT corrections are more relevant at low Q

Working at LL the solution is :

$\zeta = \mu^2 = Q^2$

$$b_T^{sp\ 0} = \frac{c}{\Lambda}\left(\frac{Q}{\Lambda}\right)^{-\Gamma_1^{\rm cusp}/\left(\Gamma_1^{\rm cusp}+8\pi b_0\right)}$$

Determination of the saddle point

$$\frac{d}{db_T}\left\{ \int_{\mu_i}^{\mu_f} \frac{d\mu}{\mu}\gamma_F\left[\alpha_s(\mu), \frac{\zeta_f}{\mu^2}\right] - K(b_T,\mu_i)\ln\frac{\zeta_f}{\zeta_i} + \ln b_T^2 + \ln\left[\sum_b C_{a/b}(x, b_T^2, \mu_i, \zeta_i) \otimes f_b(x,\mu_i)\right]\right\}_{b_T = b_T^{sp}} = 0$$

Generate the **scale-dependence** of the saddle point

Generates the **x-dependence** of the saddle point

Qiu, Zhang (2001) introduced the x-dependent term in the analysis at the level of the cross section.

We repeat the same at the level of the TMD PDF, using the language of TMD evolution

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Determination of the saddle point

$$\frac{d}{db_T}\left\{\int_{\mu_i}^{\mu_f}\frac{d\mu}{\mu}\gamma_F\left[\alpha_s(\mu),\frac{\zeta_f}{\mu^2}\right]\right.$$

Generate the **scale-dependence** of the saddle point

$$-K(b_T,\mu_i)\ln\frac{\zeta_f}{\zeta_i}$$

$$+\ln b_T^2$$

Generates the **x-dependence** of the saddle point

$$\left.+\ln\left[\sum_b C_{a/b}(x,b_T^2,\mu_i,\zeta_i)\otimes f_b(x,\mu_i)\right]\right\}_{b_T=b_T^{sp}}=0$$

Working at LL the solution is :

$$b_T^{sp}=\frac{c}{\Lambda}\left(\frac{Q}{\Lambda}\right)^{-\Gamma_1^{\rm cusp}/\left[\Gamma_1^{\rm cusp}+8\pi b_0\left(1-\mathcal{X}(x,\mu_b^\star)\right)\right]}$$

$$\mathcal{X}(x,\mu)=\frac{d}{d\ln\mu^2}\ln f_a(x,\mu)\qquad\qquad \zeta=\mu^2=Q^2$$

$$\mu_b^\star=2e^{-\gamma_E}/b_T^{sp}$$

Requires iterative solution

Conclusion : the predictive power is governed by both Q and x

The sign of the derivative of the collinear PDF determines the behavior

Large b_T corrections

$$f_1^a(x, b_T^2; Q) = \begin{cases} f_1^a(x, b_T^2; Q) & b_T \leq b_{max} \\ f_1^a(x, b_{max}^2; Q) F^{NP}(x, b_T, Q; b_{max}) & b_T > b_{max} \end{cases}$$

Calculable in pQCD (modulo PDFs)

To be modeled and fit to data!

Which one is the most **relevant** part and in which **kinematic region**?

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Large b_T corrections

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$$F^{NP}(x, b_T, Q; b_{max}) = \exp\Big\{ - \ln\left(\frac{Q^2 b_{max}^2}{c^2}\right)\{g_1[(b^2)^\alpha - (b_{max}^2)^\alpha]\} - \ln\left(\frac{Q^2 b_{max}^2}{c^2}\right)\{g_2(b^2 - b_{max}^2)\} - \bar{g}_2(b^2 - b_{max}^2)\Big\}$$

"**extrapolation term**" (see also Qiu-Zhang PRD63 114011)

low bT behavior extrapolated to large bT region

g_1 , α

fixed as a function of the other parameters, requiring continuity of the first and second derivatives

Large b_T corrections

$$f_1^a(x,b_T^2;Q) = \begin{cases} f_1^a(x,b_T^2;Q) & b_T \le b_{max} \\ f_1^a(x,b_{max}^2;Q)\,F^{NP}(x,b_T,Q;b_{max}) & b_T > b_{max} \end{cases}$$

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"**extrapolation term**" (see also Qiu-Zhang PRD63 114011)

Correction to evolution

g_1 , α

fixed as a function of the other parameters, requiring continuity of the first and second derivatives

Large b_T corrections

$$f_1^a(x, b_T^2; Q) = \begin{cases} f_1^a(x, b_T^2; Q) & b_T \le b_{max} \\ f_1^a(x, b_{max}^2; Q) F^{NP}(x, b_T, Q; b_{max}) & b_T > b_{max} \end{cases}$$

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"**extrapolation term**" (see also Qiu-Zhang PRD63 114011)

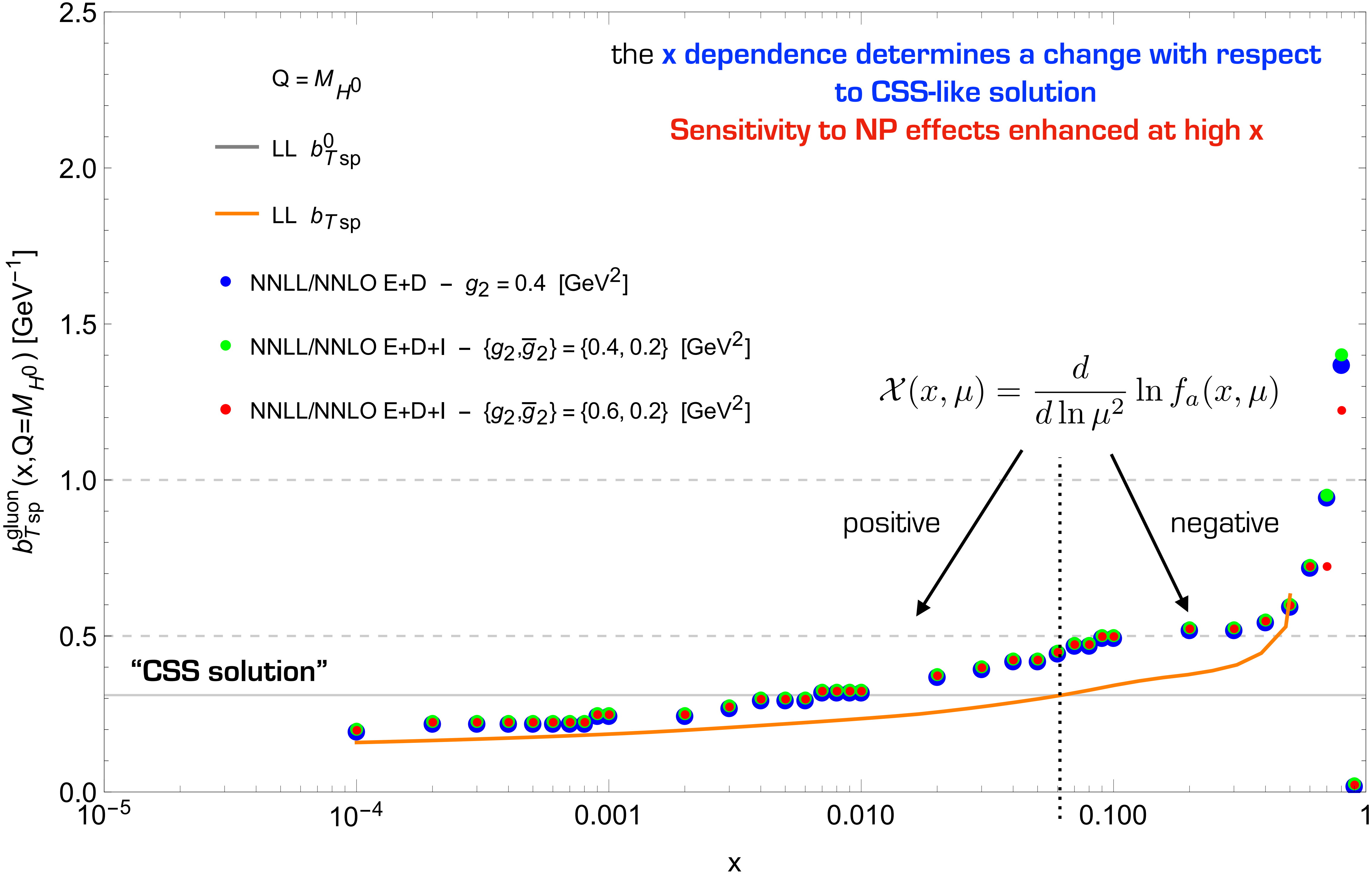
Correction to evolution

Correction to OPE at small bT (intrinsic transverse momentum)

g_1 , α **fixed** as a function of the other parameters, requiring continuity of the first and second derivatives

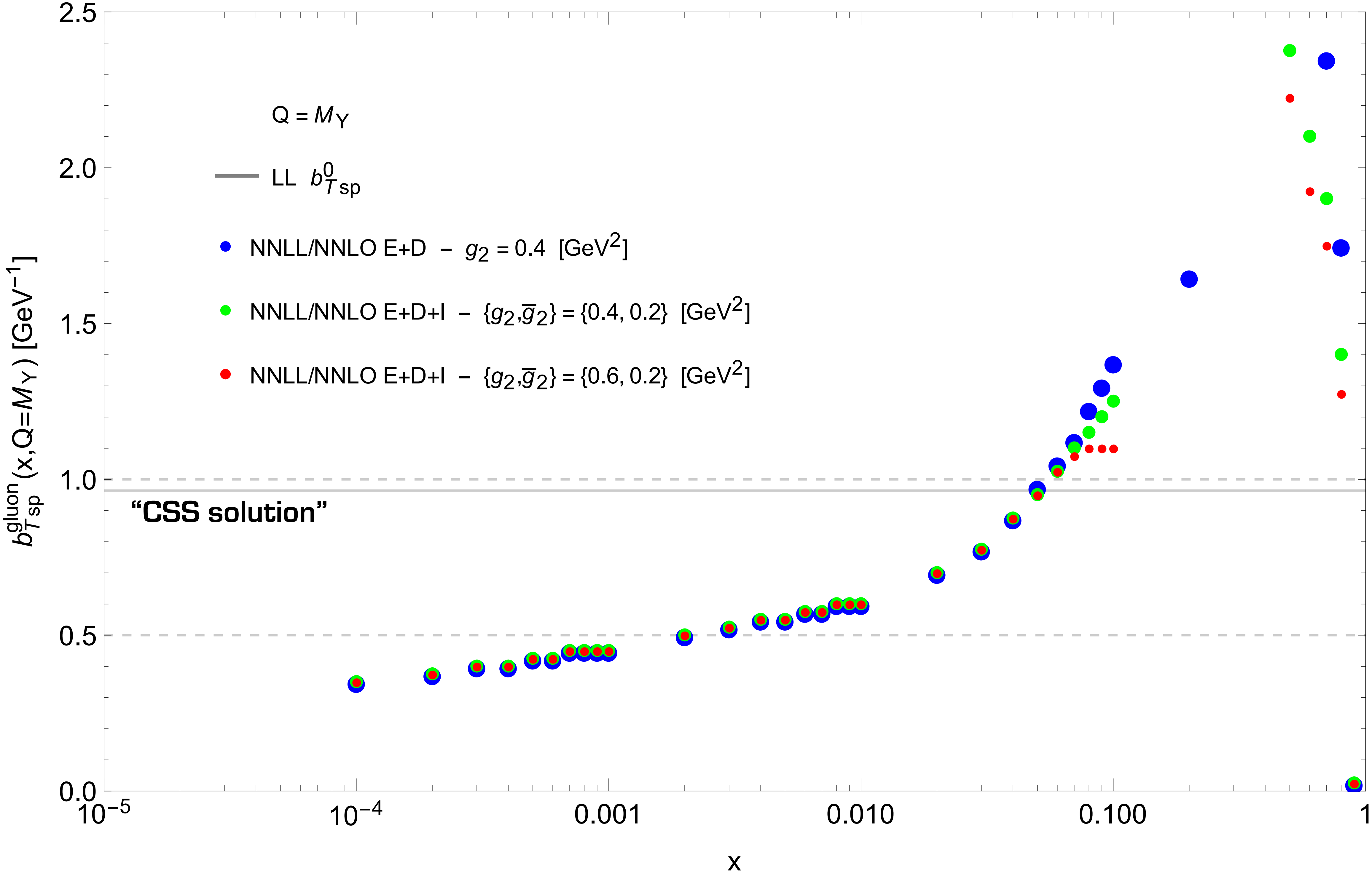
gluon - M_H (~125 GeV)

preliminary



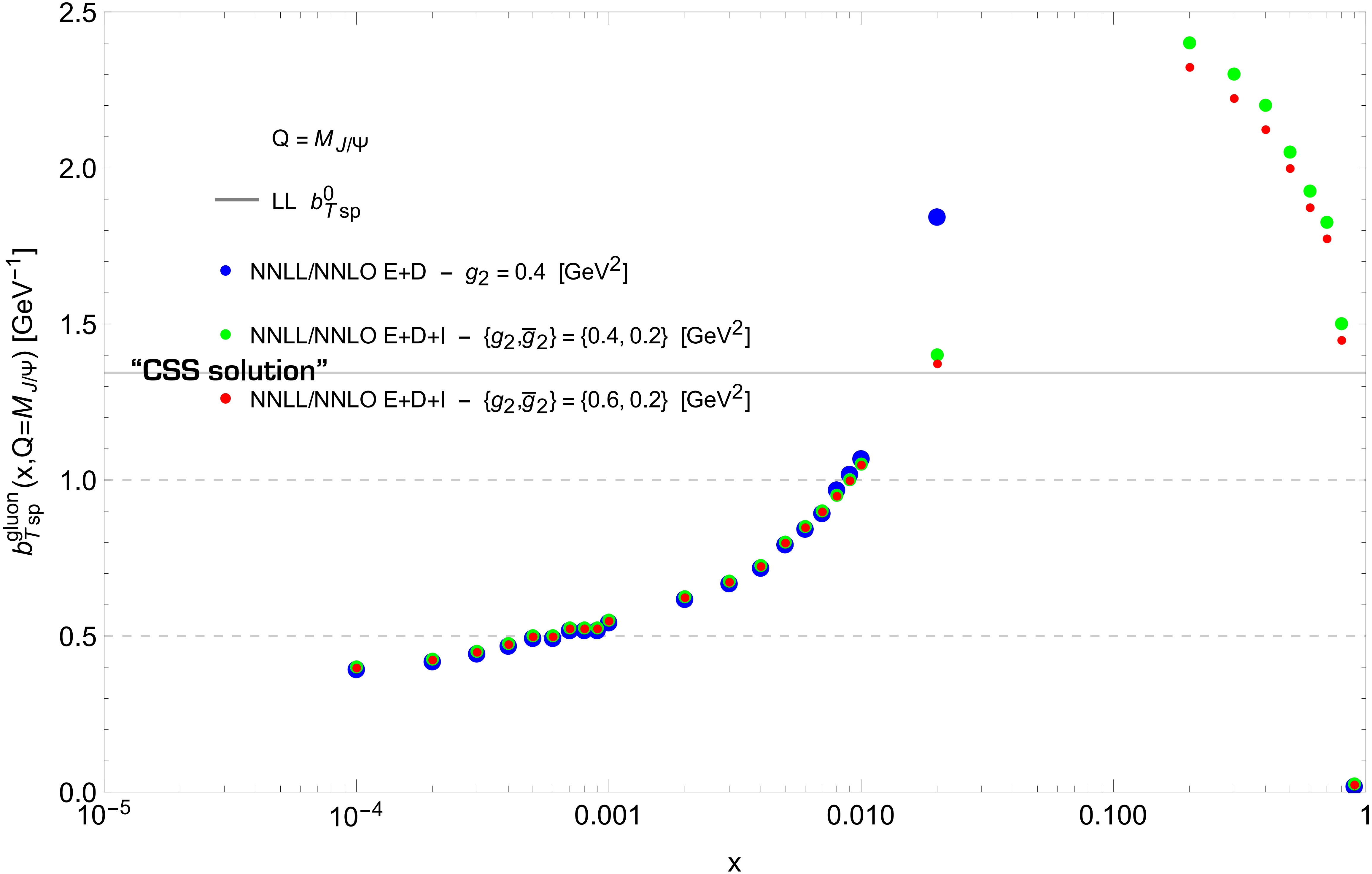
gluon – M_Υ (~9 GeV)

preliminary



gluon – $M_{J/\psi}$ (~3 GeV)

preliminary



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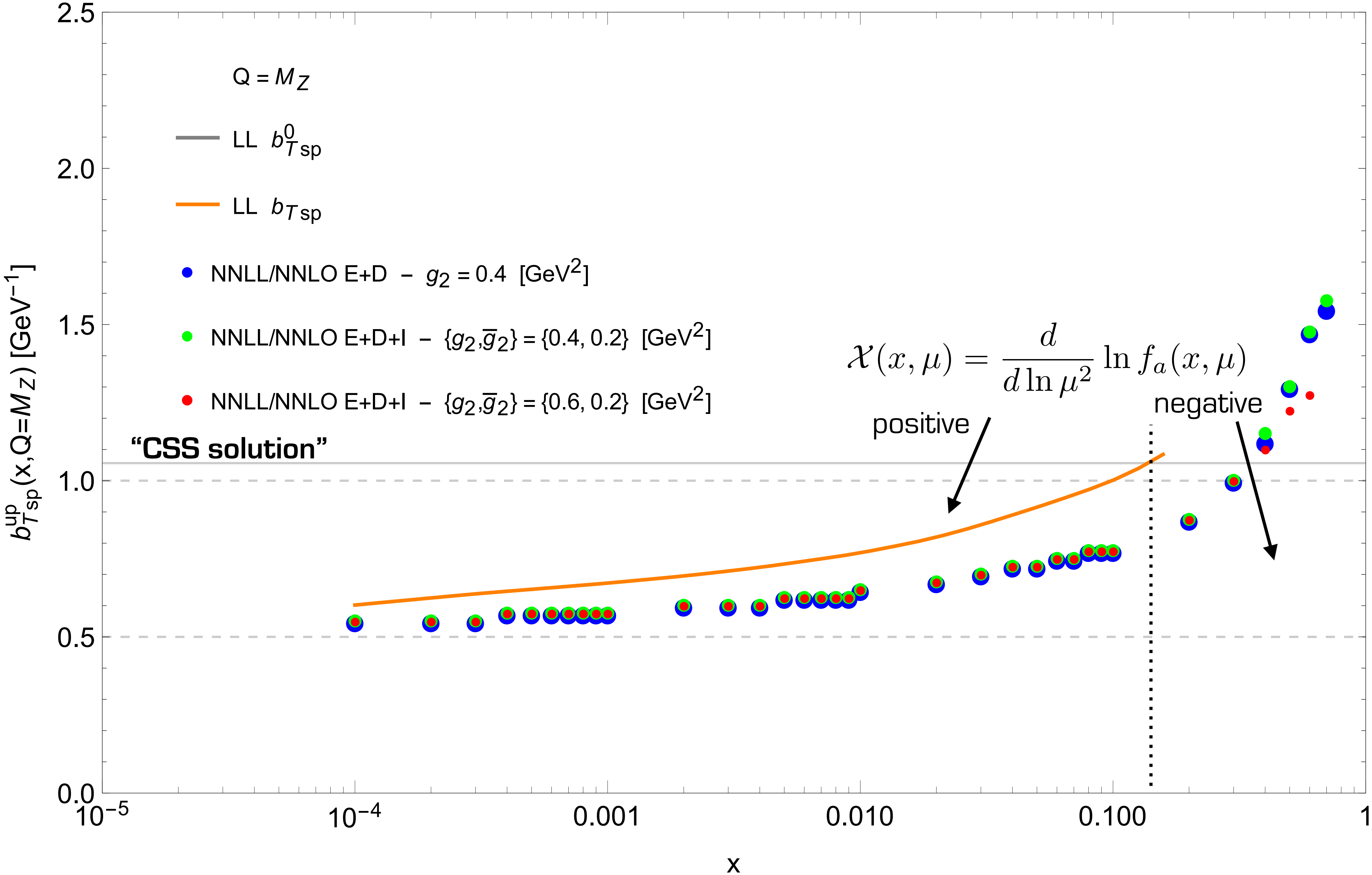
up quark – M_Z (~91 GeV)

preliminary



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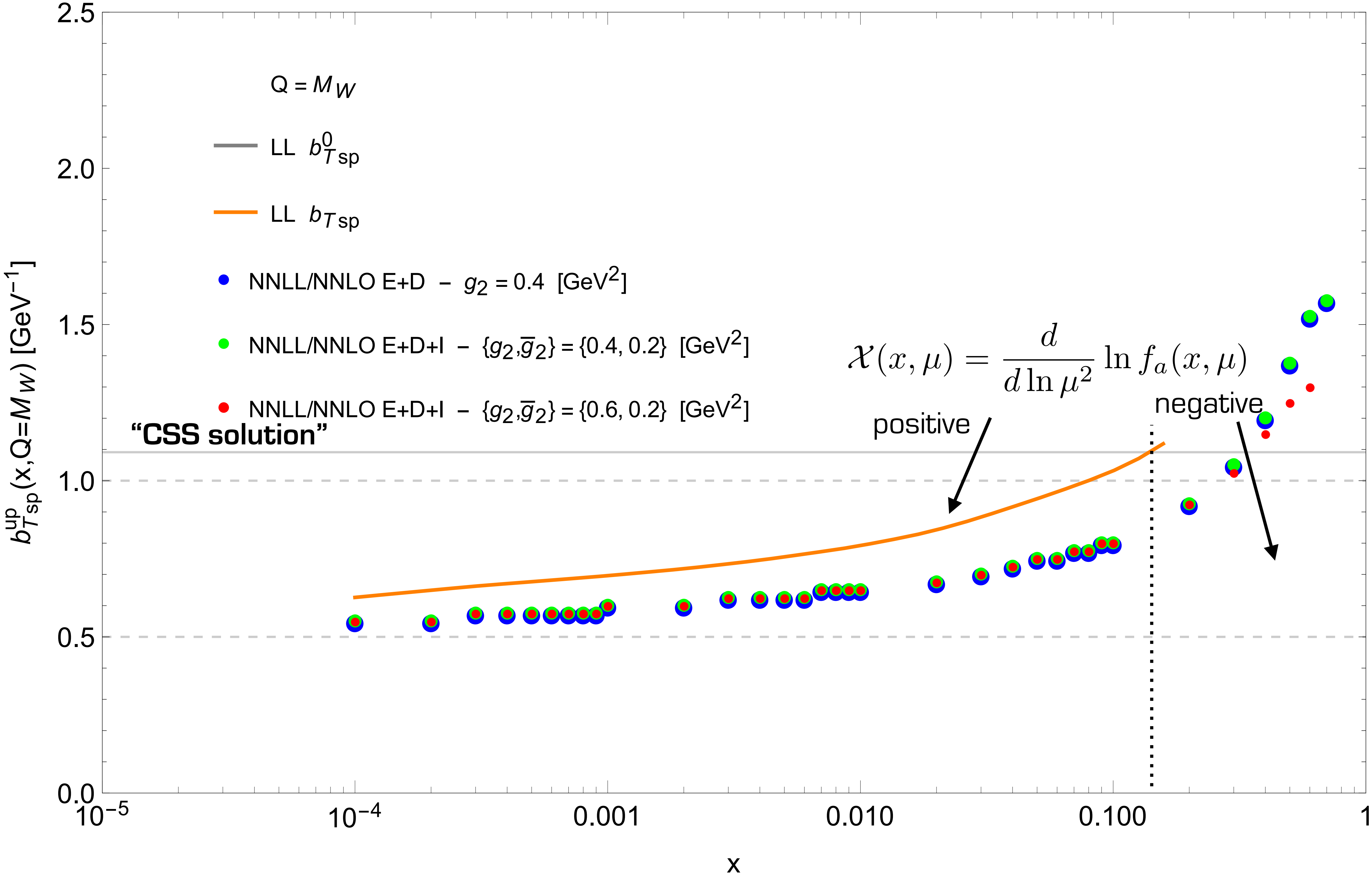
up quark – M_W (~80 GeV)

preliminary



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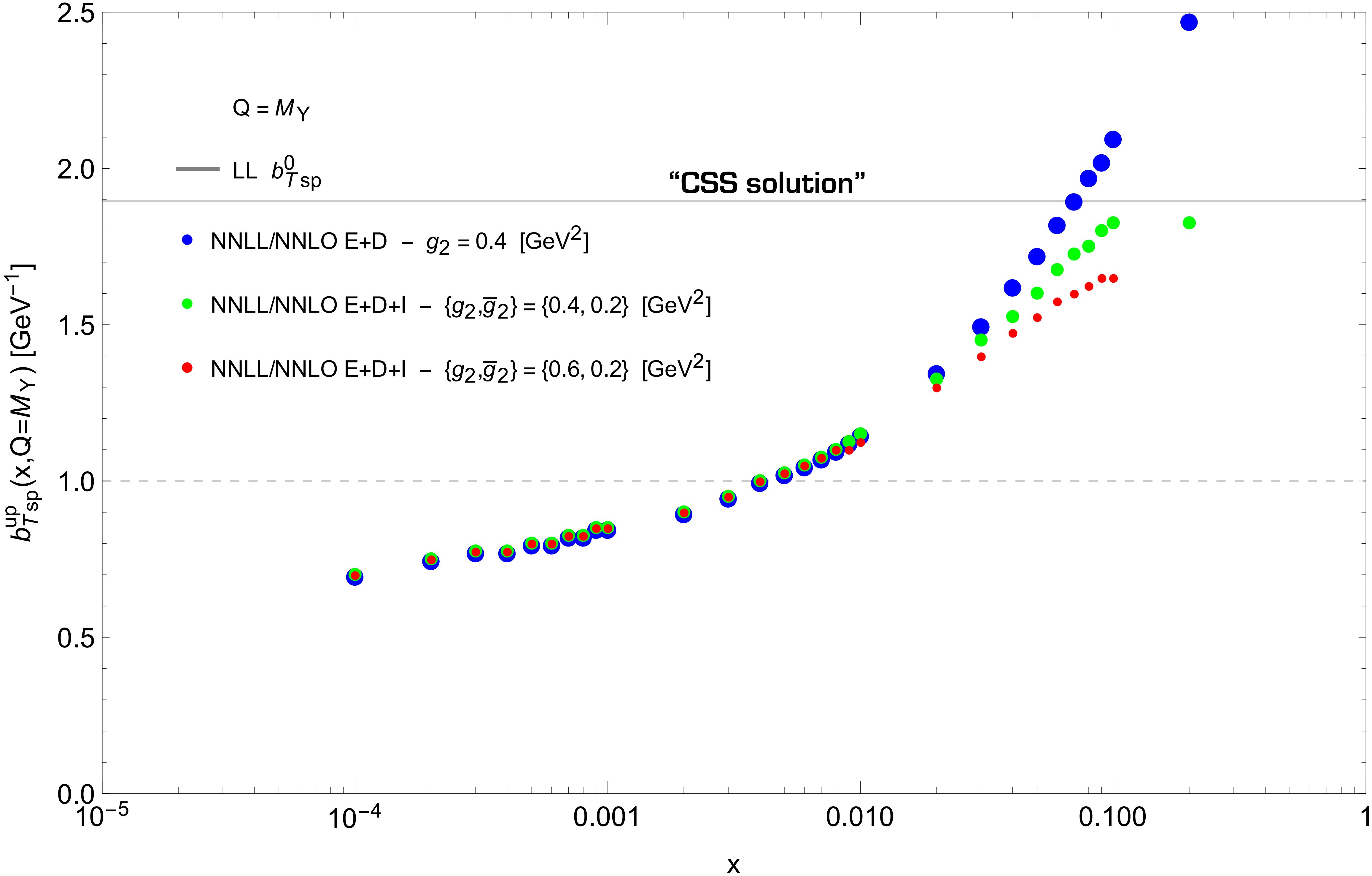
up quark – M_Y (~9 GeV)

preliminary



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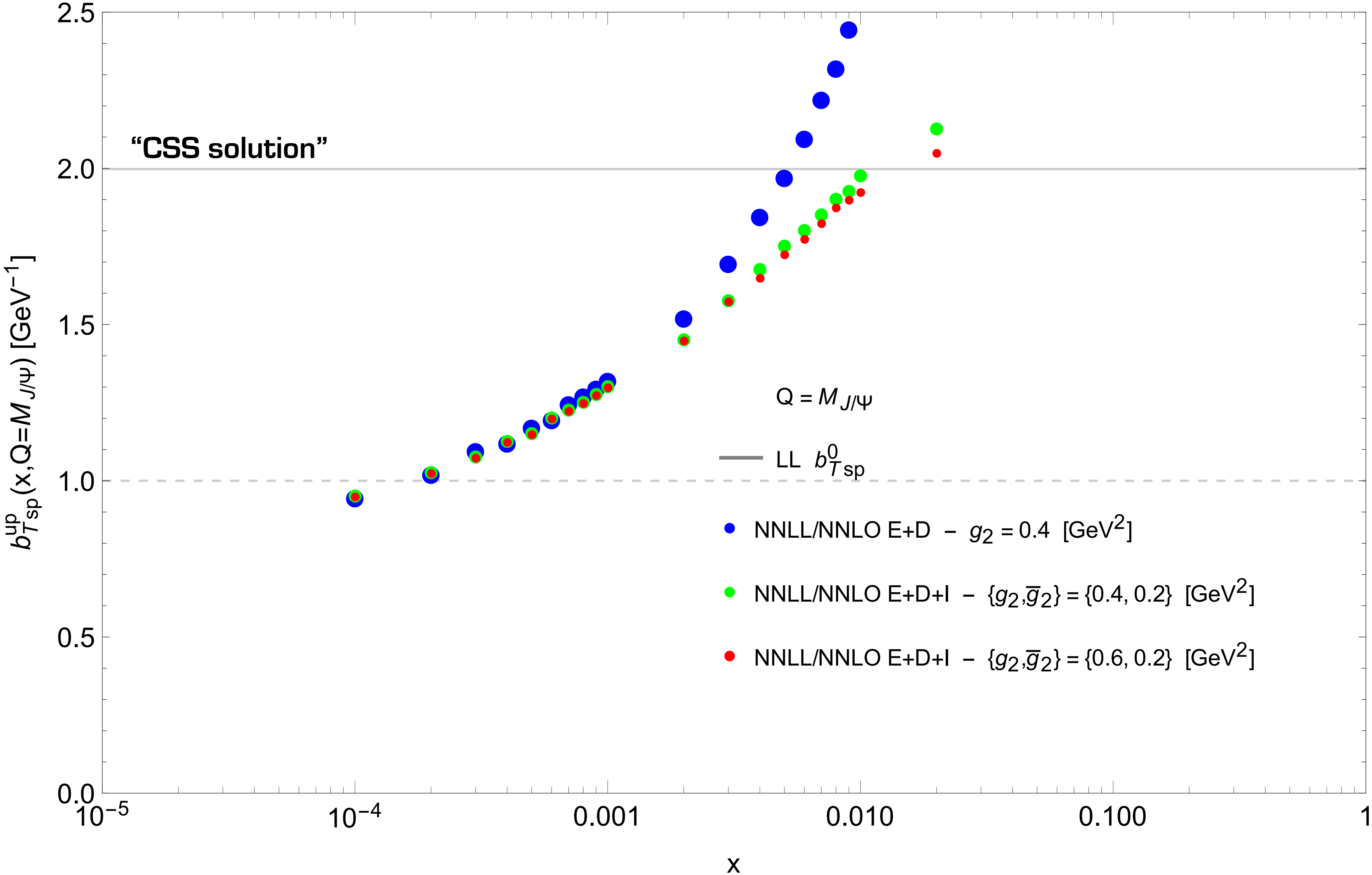
up quark – $M_{J/\psi}$ (~3 GeV)

preliminary



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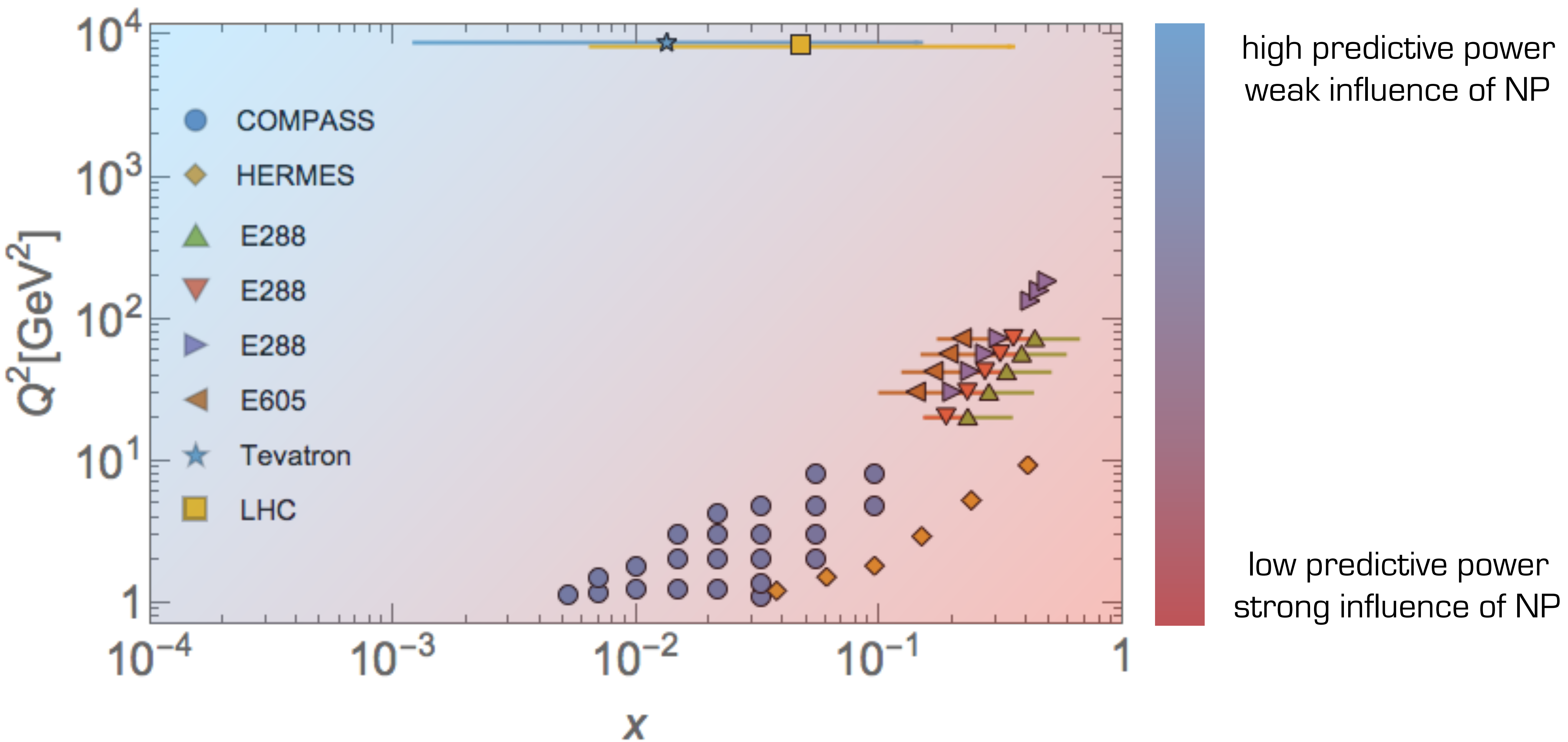
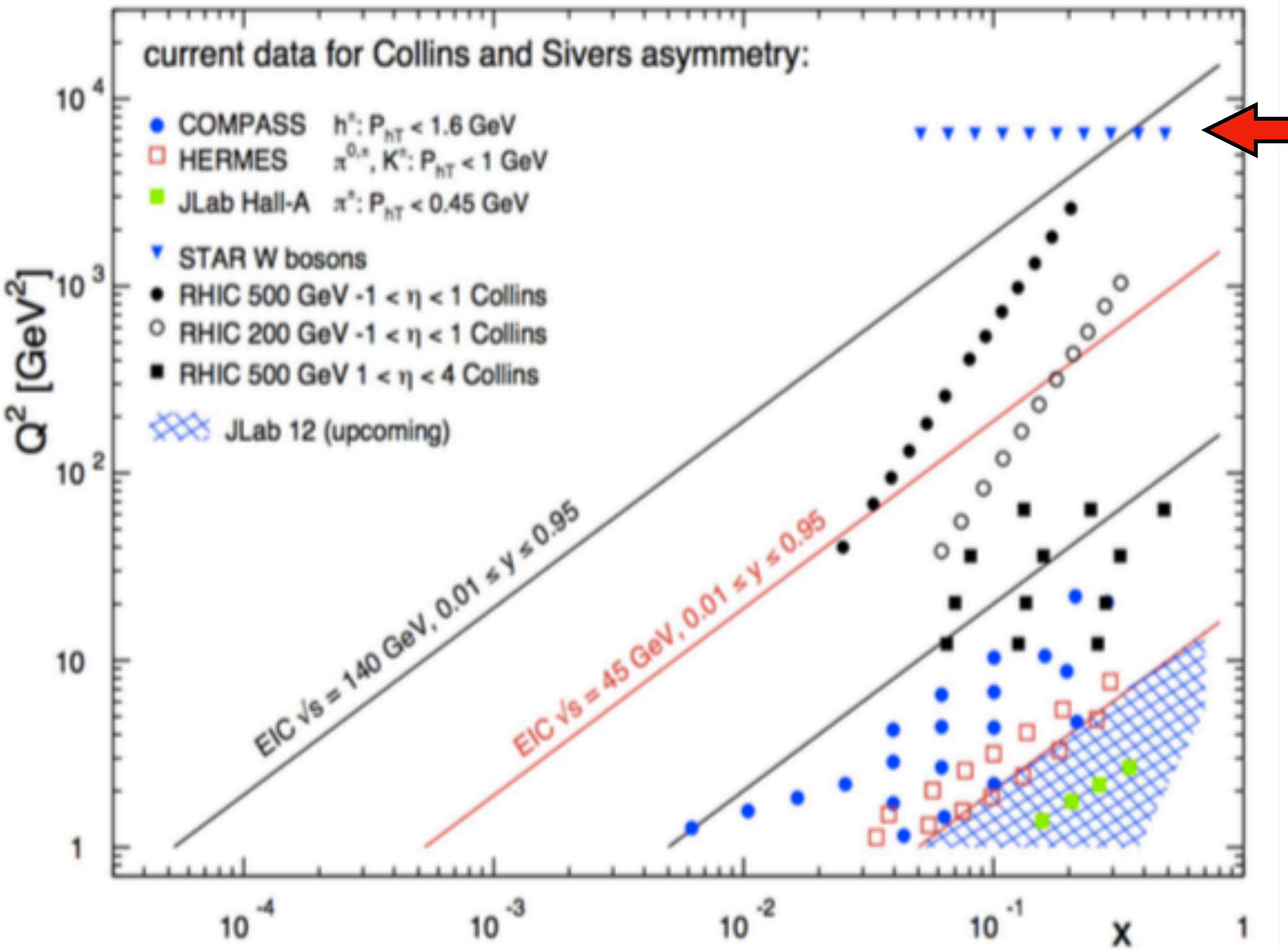
Predictive power in x-Q plane



Small-x, high-Q :
strong predictive power

Rapidity dependence too

Kinematic coverage



W-boson production at RHIC probes TMDs in the high Q - high x region

High Q : TMD factorization under control

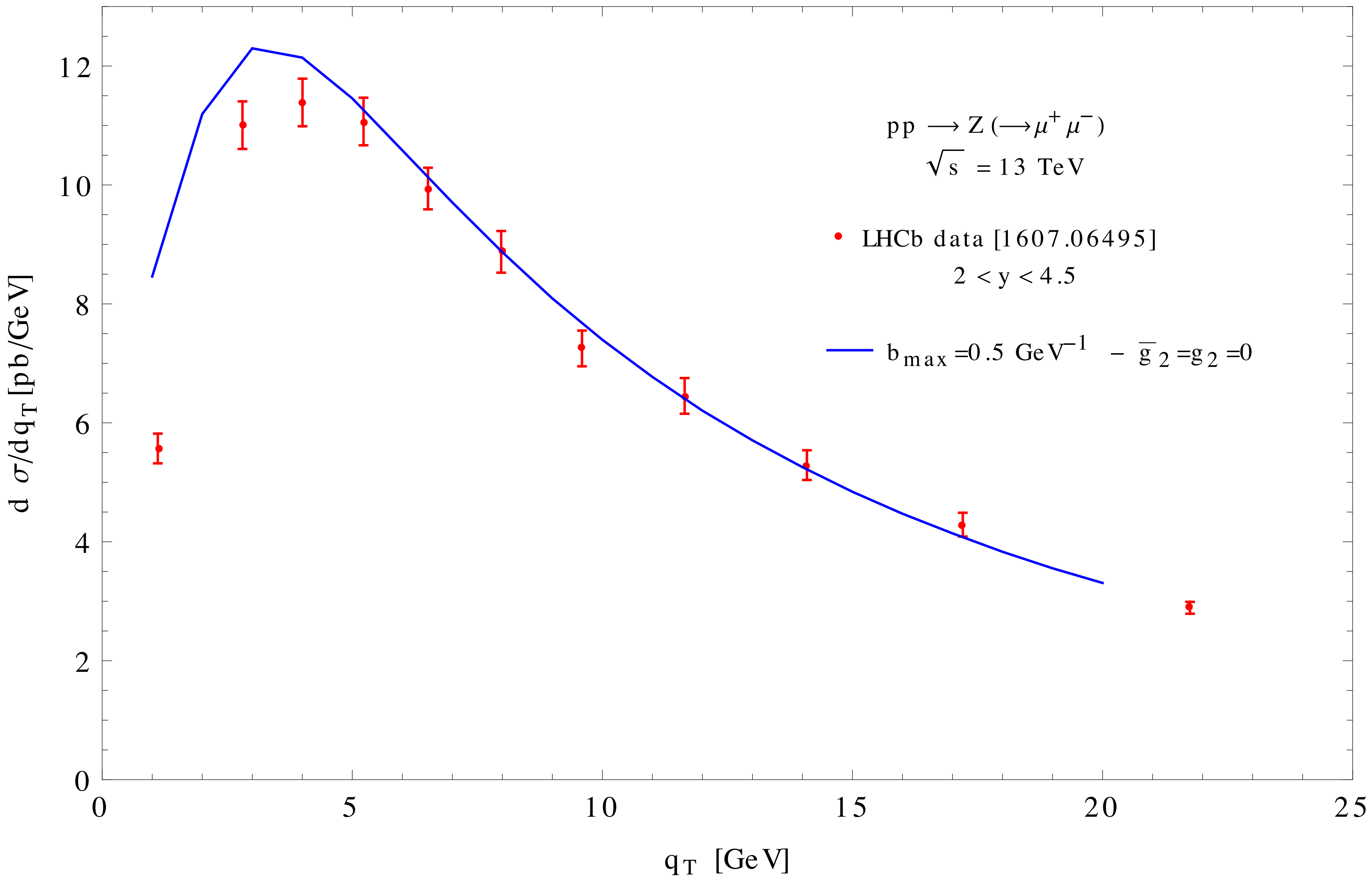
High x : enhanced sensitivity to nonperturbative effects

Interesting combination

Picture from O. Eyser - CIPANP 2018

Z production @LHC 13 TeV

preliminary



High-Q / high-s

Forward rapidity

Extrapolation to large bT without NP corrections

Forward rapidity probes significantly large x values and we need NP corrections to describe the very low qT bins

The **more precise the observable** is, the more **relevant** the **NP corrections** can be: see e.g. W mass and flavor dependence of intrinsic transverse momentum (arXiv:1807.02101)

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Conclusions and outlook

A first attempt to a **global fit of TMD PDFs and FFs** has been completed
We need independent information about TMD FFs to break the anti correlation with TMD PDFs

TMDs have predictive power in the small-x / high-Q limit.
Z production @LHC 13 TeV in different rapidity ranges can be used to prove the point.
Forward rapidity probes large x region, which implies sensitivity to the form of the NP part.

Conversely observables are more sensitive to NP corrections in the low-Q / large-x limit (**JLab**).

An interesting region to **extract the nonperturbative contributions** to TMD PDFs could be the region at **high Q** (to better control the corrections to factorization) and **high x** (to enhance the sensitivity to the large bT region)
RHIC can provide data in this region, e.g. **W-boson production** to study both **polarized and unpolarized TMDs**, providing a complementary view on the results available from JLab

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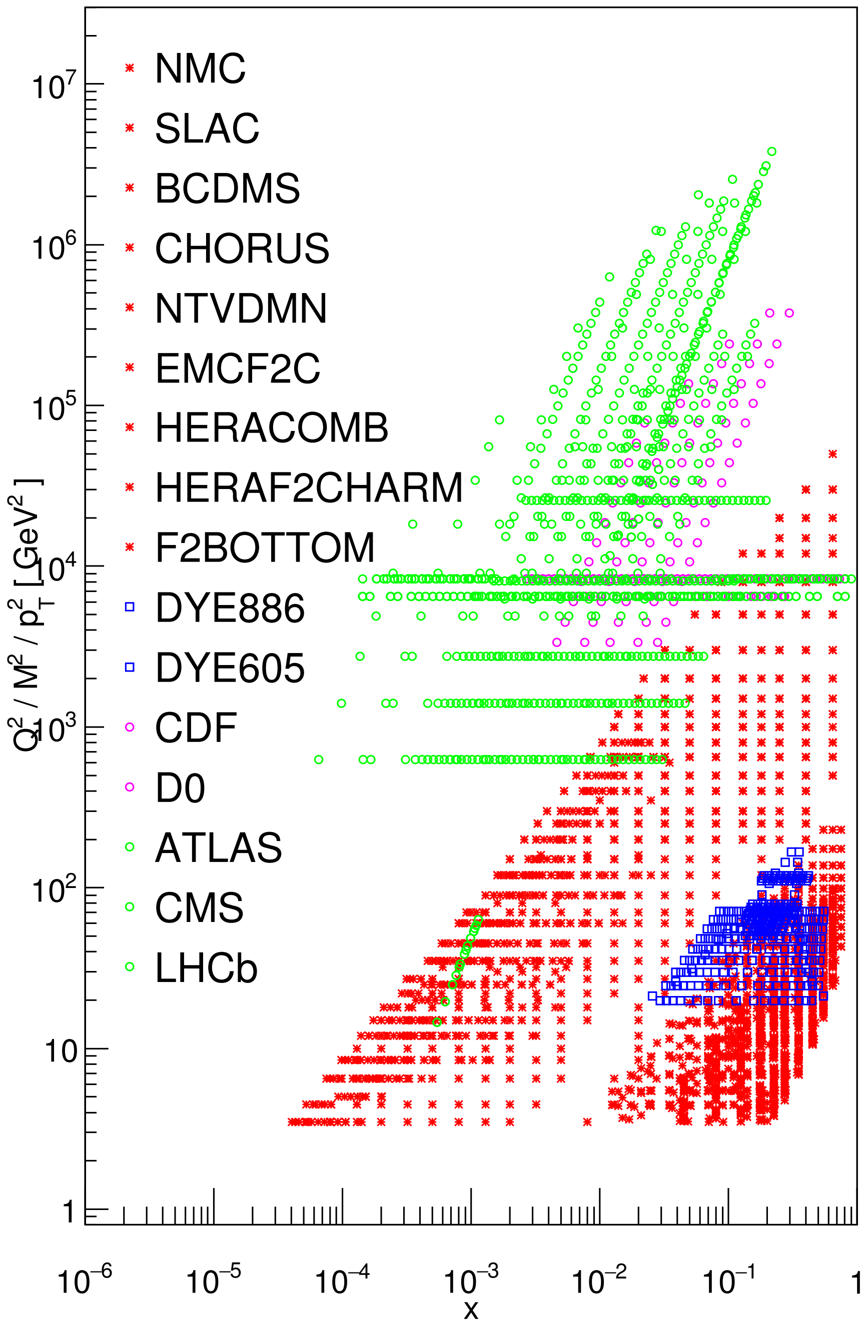
Backup

Collinear vs TMD PDFs

see E. Nocera - POETIC2016



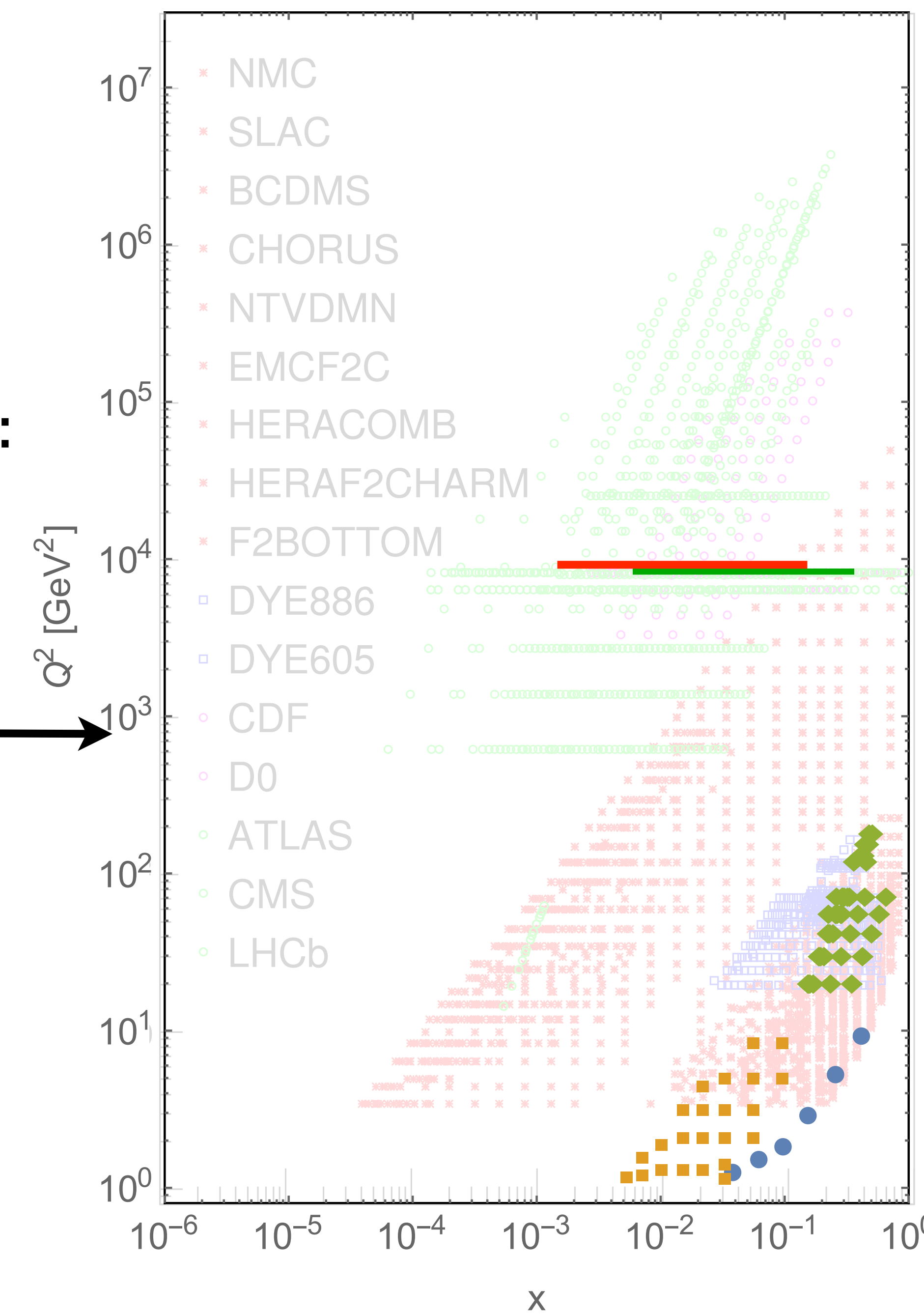
data driven science

data sets available:

collinear PDFs

vs

TMD PDFs



Q : resolution of the probe

x : momentum fraction carried by the parton

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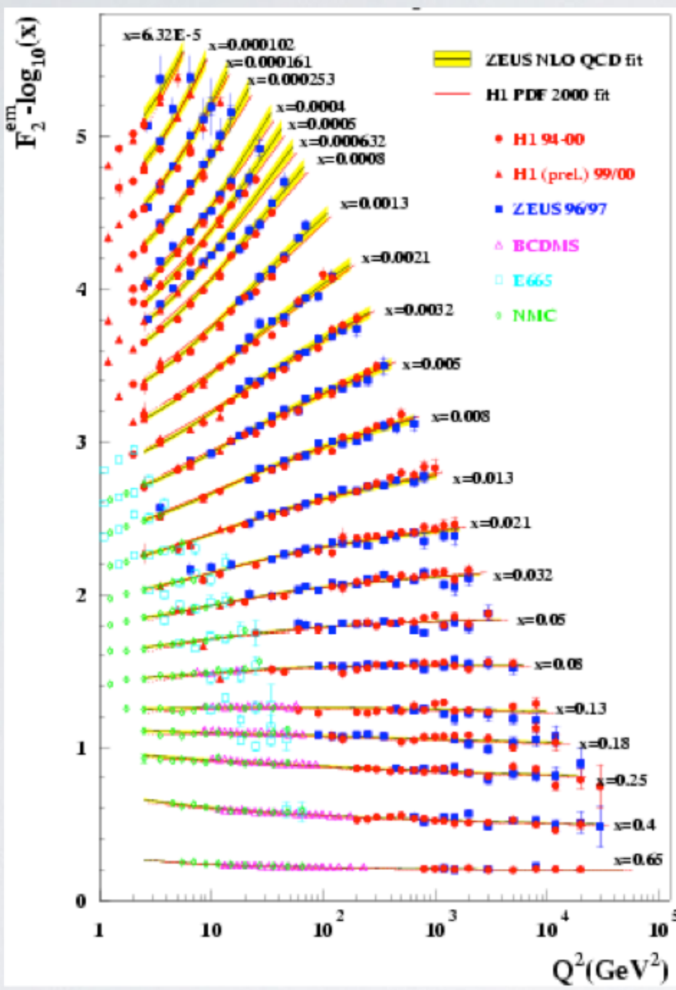
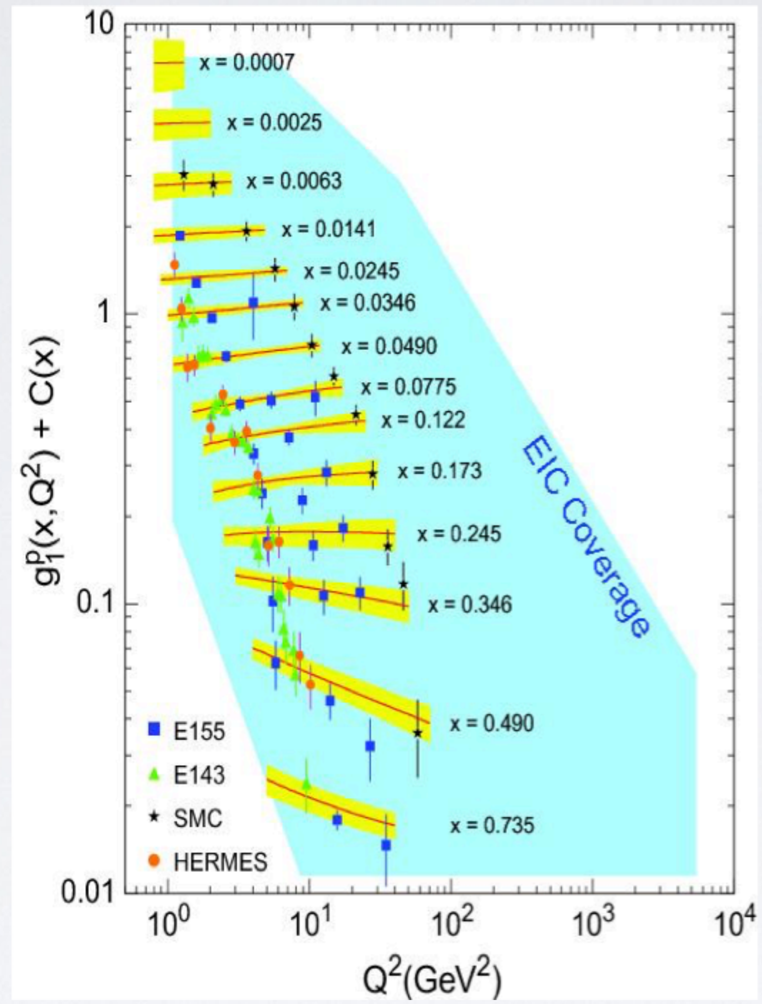
(Un)polarized collinear PDFs

World data for F_2^p



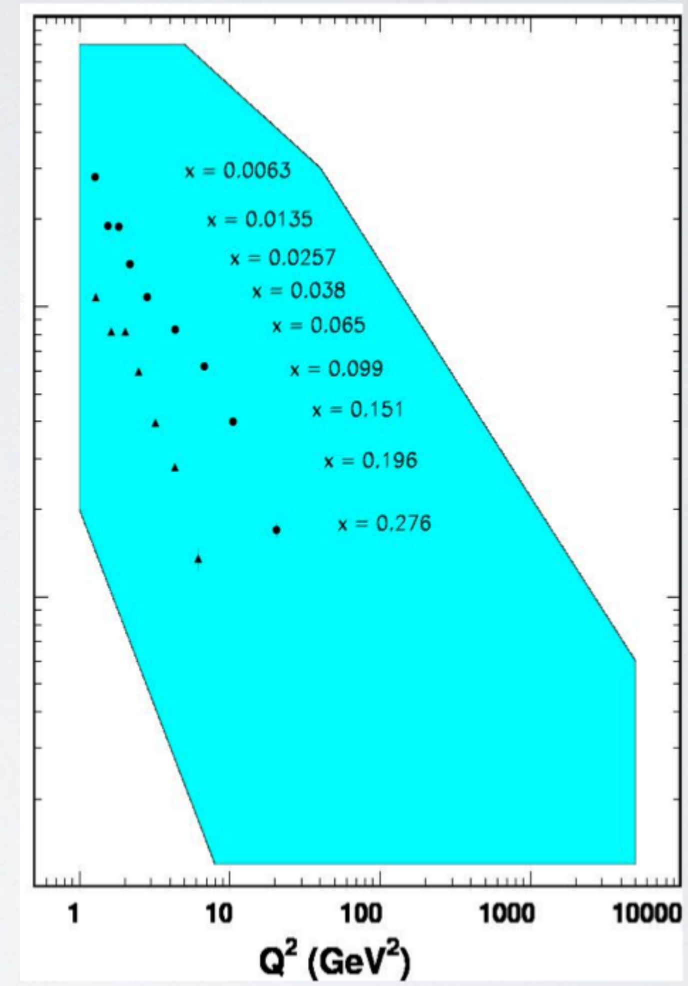
f_1 from fits of **thousands** data

World data for g_1^p



g_1 from fits of **hundreds** data

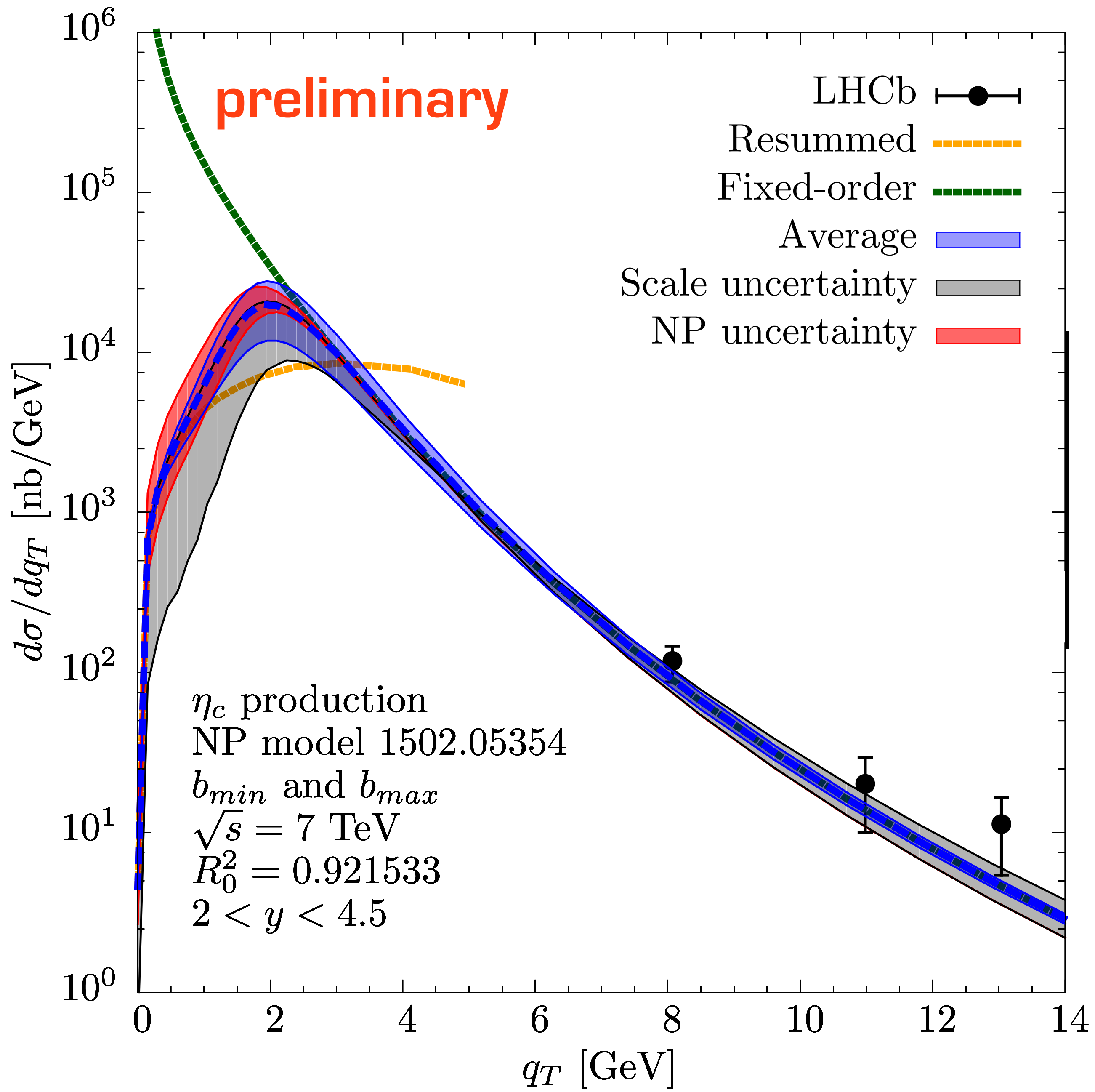
World data for h_1



h_1 from fits of **tens** data

η_c production at LHC

full transverse momentum spectrum: inverse-error weighting :



Echevarria, Kasemets, Lansberg, AS, Pisano
Phys.Lett. B781 (2018) 161-168

blue band: uncertainty from matching

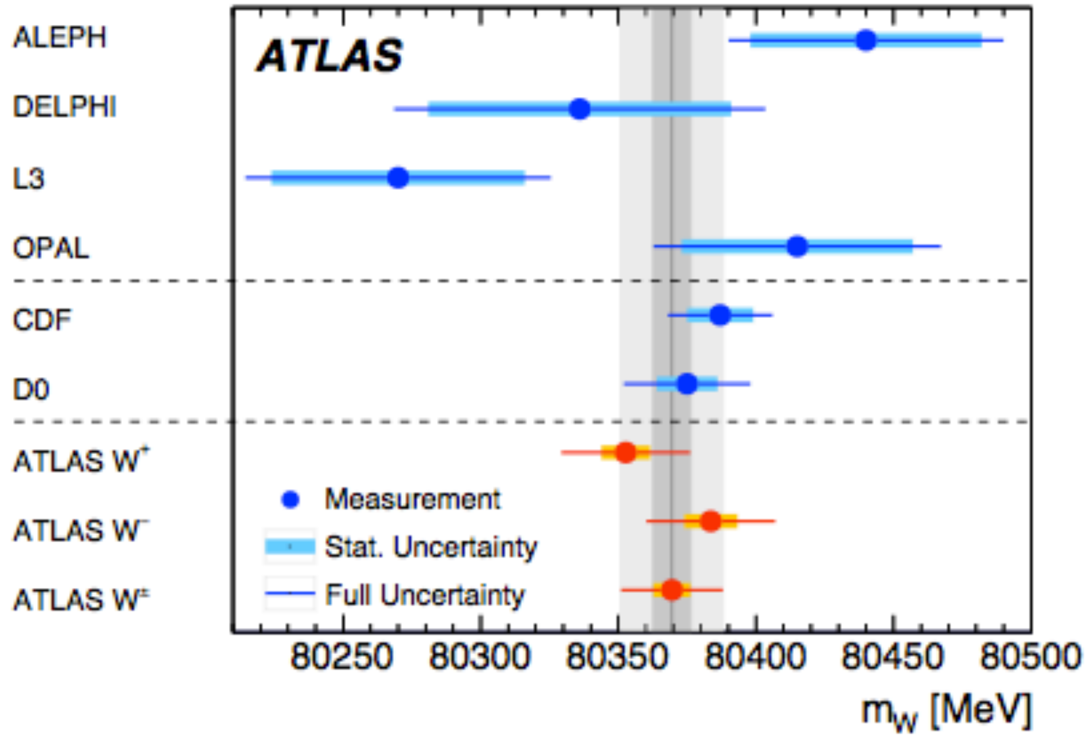
grey band: scale uncertainty

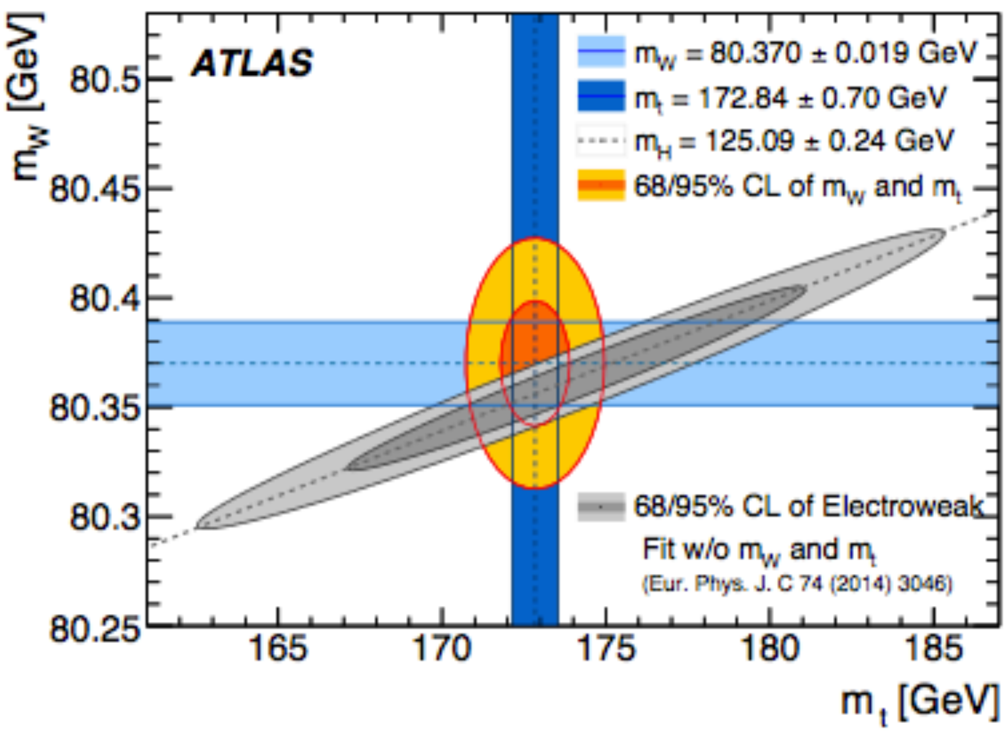
red band: uncertainty associated to the nonperturbative evolution and intrinsic transverse momenta

the formalism is in good shape
we need the data at low q_T

W mass

ATLAS, arxiv:1701.07240





Experimental measurements

$$m_W = 80370 \pm 19 \text{ MeV}$$

(7 stat, 11 exp, 14 th)

Global EW fit

$$m_W = 80356 \pm 8 \text{ MeV}$$

Need to **better control the uncertainties** associated to **direct** determinations of mW →

Is it possible to reduce the uncertainty to less than 10 MeV ?

Are we estimating all the **uncertainties of hadronic nature** in the best way possible?

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